STUDY OF CURRENT CONTROL INVERTER FED INDUCTION MOTOR DRIVES

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"एक प्रयास !
मम्मी और पापा के चरणों में"

CERTIFICATE

:rtified that the work entitled 'STUDY OF CURRENT CONTROL IVERTER FED INDUCTION MOTOR DRIVES' which is being bmitted by Mr. Vijay Pratap Singh in partial fulfilment the award of the degree of Master of Technology, has en carried out under our supervision and guidance. The tter presented in this thesis, has not been submitted sewhere for a degree.

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ABSTRACT

The ac motors, particularly squirrel cage induction motor, have a number of advantages in comparison to either dc or synchronous motors. However, under certain conditions, a current/frequency controlled induction motor drive operating either as a motor (or as a generator) can exhibit self-sustained oscillations about a steady-state operating point. At the same time the induction motor is a difficult device to model.

Analysis of current control inverter fed induction motor using d-q model has been done. The feasibility of developing controlled current induction motor drives using transfer function techniques has also been studied. A systematic study of several controllers in a current source inverter fed induction motor drive and their effects on the dynamic response and stability of the system has been carried out in the present work.

It has been shown, that, the system may or may not be stable for various operating points for a given controller gain. Use of adaptive control has been suggested.

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LIST OF SYMBOLS

Subscripts

O	steady state quantity as in i'^{e}_{dro}, orthogonal,
d or q	equivalent 2-phase transformed variable as in i^{e}_{ds}
b	base quantity as in ω_b,
e	electrical quantity as in ω_e,
F	smoothing choke parameters as in R_F',
I	inverter quantity as in V_I,
m	mutual value as in x_m,
l	leakage quantity,
r	rotor quantity as in x_r,
R	rectifier quantity as in V_R,
s	stator quantity as in x_s, slip,
sl	slip quantity as in ω_{sl},
g	air-gap,
av	average,
max, m	maximum
C	dissipation
mech	mechanical,
a	phase a,
b	phase b,
c	Phase c,
park	Transformed variable
L	Load.

Superscripts

*	command values as in ω_r*,
'	rotor quantity referred to the stator,
e	quantities in synchronously rotating reference frame as i'^{e}_{dr}.

Variables

N	effective turns,
r	resistance,
L_l	leakage inductance,
L	self-inductance,
x	Reactance,
Z	impedance,
f	frequency,
K_w	winding factor,
ϕ	Flux,
ω_{sl}	slip speed,
ω	electrical angular speed,
I	current,
V	dc voltage,
T	Torque,
α	firing angle,
θ	Instantaneous angular displacement of the arbitrary reference frame,
θ_r	Angular displacement between the stator and rotor phases,
f	Represents either voltage, current or flux linkage,
n	number of phases,

λ	Total flux-linkages of a particular winding,
L_{sm}	Mutual inductance between stator phases,
L_{rm}	Mutual inductance between rotor phases,
L_{sr}	The amplitude of the mutual inductance between stator and rotor windings,
	perturbation variable,
τ	current regulator zero location,
J	system inertia,
K_1	current regulator gain,
K_2	Speed regulator gain,
p	differential operator d/dt,
P	machine poles, power,
Q	output of integral controller,
$\cong$	Approximately equal to,
L_F	filter inductance
R_F	filter resistance
B_r	flux density
$\sim$	Proportional to

CHAPTER 1

INTRODUCTION

In the past, usually ac motors have been used in the applications requiring constant speed. In variable speed applications, mainly dc motors, especially of shunt type, have been used. The development of power electronic devices, first the thyristor and more recently the gate turn-off thyristor (GTO) and the power transistor has freed ac electronic motors from this constraint of a fixed (i.e. synchronous) speed. With the improvement in capabilities and reduction in cost of these devices, it has become possible to build ac drives which can match dc drives in performance as well as in cost. As a result of this, ac drives have succeeded in replacing dc drives in a number of variable speed applications.

The ac drives compete directly and favourably with the traditional dc drives and they can provide superior performance, faster response, greater bandwidth and greater overload capability. These features are particularly attractive to the machine tool industry and it is in this area that the greatest technical advances has been made. It is possible now to make very simple, rugged and relatively inexpensive ac drives and these have brought the advantages of variable speed to operations such as water and sewage pumping system which could not justify the cost of traditional dc drives.

The ac motors, particularly squirrel cage induction motor, have a number of advantages in comparison to either dc or synchronous motors. Some of these are, lower maintenance, cost, weight, volume and inertia, ruggedness, higher efficiency and improved reliability. The squirrel cage induction motor, having no sliding contacts, can be totally enclosed and, if need be, made flameproof. It can be employed in hazardous and hostile environments. The major drawback of dc motors is the presence of commutator brushes and sliding contact between them, which require frequent maintenance and repair and this makes dc motors unsuitable for explosive and unhealthy environment.

Inverters permit the generation of three-phase ac over a wide range of power frequencies. Most inverters in present use can be designated controllable-voltage adjustable-frequency source, since the output terminal voltage is essentially independent of current. Recently, however, the useful features of inverters in which the current rather than voltage appears essentially as the independent variable, have been recognized. Since a larger portion of electrical equipment which utilizes ac power over a range of frequencies requires current of approximately constant magnitude, this type of inverter appears to have inherent advantages. Typical applications include ac motor drives which are controlled to develop constant motor torque over a fixed speed range. In addition, the current source inverter (CSI) has many advantages which make it an attractive alternative to conventional controllable-voltage source inverters.

The CSI is a very rugged supply capable of recovery from short circuits or commutation faults. It offers inherent overcurrent protection when current feedback is used. It is a simple circuit which does not require fast turnoff thyristors. The CSI is capable of full regeneration with only 12 SCR's and 6 diodes. While it produces a square wave current supply, the motor voltage and hence flux is quasi-sinusoidal. It is cheap and simple to design current source inverter. These numerous advantages have resulted in increasing use of the current source inverter drives.

However, under certain conditions, a current/frequency controlled induction motor drive operating either as a motor or as a generator can exhibit self-sustained oscillations about a steady-state operating point. These oscillations are actual instantaneous rotor speed changes accompanied by variations in output torque, motor current and input power. This operating point instability is directly related to the machine, load and other system parameters. The open-loop operation of current source inverter fed induction motor is unstable for most operating conditions and therefore control loops must be added to realize feasible operating points. For these drives, feedback loops are added for improved regulation and response and also for protection purposes. The presence of open-loop instability, makes design of the closed-loop control by purely laboratory techniques, a

difficult task. All this has prompted us to go into the causes, method of analysis and means of eliminating this instability problem. We will study an analytical design technique for finding the transfer function between a specific input command and a controlled output variable, based on small-signal linearization. In order to assess or design outer control loops such as speed or torque controllers, it is necessary to have a simple but reliable model for the inverter, the induction-motor and any inner loops which might be considered as basic to the drive. The induction motor is a difficult and complicated device to model because of the many nonlinearities present. Besides, the addition of the inverter power supply adds other non-linearities. Therefore, we will study the systematic development of such a model.

In 1968, BORIS [1] developed theory and control technique for the controlled slip static inverter drive. Later, LIPO and KRAUSE [2,3] in 1969, studied the stability of a rectifier - inverter induction motor drive. They developed a method for determining the stability of a rectifier-inverter induction motor drive system. They also investigated the effect of the system parameters on system stability using Nyquist stability criterian.

The exact equations defining steady-state operation of a controlled current induction motor drive system using state-variable approach were developed by LIPO and CORNELL [4] in 1975.

They showed, that, normal open-loop operation occurs on the unstable side of the torque-slip characteristic necessitating the use of feedback control for stable operation.

SAWAKI and SATO [5] in 1977 studied and compared the steady-state characteristics and instability of an induction motor driven by current source inverter with the system driven by voltage source inverter. They applied Routh-Hurwitz criterion to determine several instability boundaries for various parameters.

A dynamic model for current-controlled induction motor drives was developed by CORNELL and LIPO [6] in 1977. They formulated a transfer function approach to the transient response investigation by means of d-q variables in the synchronously rotating reference frame.

In 1979, SEN [7], studied the various control loops in a current source inverter-induction motor drive and their effects on the dynamic response and stability of the system. The author developed d-q model [8] which incorporates the induction motor and the inverter power supply with current feedback.

The basic idea of the control methods implemented in the present work has been taken from the reference [7] in which various control techniques have been discussed. Faddeeva's method [27] has been used to develop transfer function for various input and output variables.

The present work is organised into five chapters, including the current one, as detailed below.

The Chapter 2 presents a review of various speed control methods of induction motor. Advantages and disadvantages of various speed control methods have also been discussed.

In Chapter 3, a linear model of induction motor for varying frequency of the current source inverter has been developed using d-q variables in the synchronously rotating reference frame. A transformation similar to the Park's transformation, has been used which transforms the motor time-varying equations into time invariant equations.

In Chapter 4, the non-linear equations are linearized about an operating point. Steady state characteristic and stability analysis of an induction motor driven by current source inverter in open loop has been carried out. Analysis of closed loop drive and means of improving stability of these devices has also been done.

Finally, Chapter 5 concludes with the work reported in this thesis and also gives a brief outline of the future scope of work. The report ends with the list of references and books which have been referred in giving shape to this work.

CHAPTER 2

REVIEW OF EXISTING SPEED CONTROL METHODS FOR INDUCTION MOTOR DRIVES

2.1 INTRODUCTION:

The speed of a dc motor cannot be increased much as it is limited by extreme distortion of the air-gap flux of a weak main field caused by armature reaction and consequent poor commutation. The complex constructional features of the dc armature connected to the commutator segments also place an upper limit on the motor speed. Neither of these two limiting factors inhibit the speed of a rugged wound rotor induction motor. On the other hand, ac motors suffer from the inherent speed-constancy of the rotating field dictated by the supply frequency which is normally constant. A wide range of constant speed control is possible only by expensive circuitry using silicon-controlled rectifiers (SCRs). This chapter describes the speed control of induction motors both from rotor and stator sides. Theory and control techniques of the controlled slip static inverter has been described. It is seen that if the slip of an induction motor is constrained and controlled to values below breakdown, the motor operates with high efficiency, high power factor, and moderate current, with performance comparable to that of dc machines [1].

2.2 SPEED CONTROL OF INDUCTION MOTOR:

Various methods of controlling the speed of the induction motor [18] can be visualized by considering the following speed equation

$$\omega = (1-s)\omega_s \tag{2.1}$$

It is seen from equation (2.1), that there are two basic ways of speed control, namely, (i) slip control for fixed synchronous speed and, (ii) control of synchronous speed by suitable methods.

The relationship

$$\omega_s = \frac{2\omega}{P} \tag{2.2}$$

suggests two ways to control the synchronous speed viz., control of supply frequency and change of stator poles. The latter method gives a step control, as poles can be changed in multiples of two. Pole-changing is carried out in a squirrel-cage motor only because of number of poles both for stator and rotor must be the same and that too for two steps. Only a few standard relations [22] which will be referred while discussing speed control methods are given below.

$$I_r = \frac{V_s \angle \theta_s}{(r_s + \frac{r_r'}{s}) + j(x_{ls}+x_{lr}')} \tag{2.3}$$

$$P_g = 3I_r'^2 \frac{r_r'}{s} \tag{2.4}$$

$$T_{av} = \frac{P_g}{\omega_s} = \frac{3V_s^2}{\omega_s} \frac{r_r'/s}{(r_s+r_r'/s)^2 + (x_{ls}+x_{lr}')} \tag{2.5}$$

$$\frac{r_r}{S_m} \leq \pm \sqrt{r_s^2+(x_{ls}+x_{lr}')^2} \tag{2.6}$$

$$T_{max} = \frac{3}{2\omega_s} \frac{V_s^2}{r_s \pm \sqrt{r_r'^2 + (x_{ls}+x_{lr})^2}} \tag{2.7}$$

$$P_c = P_g - P_{mech} = (\omega_s - \omega)T_{av} = S\omega_s T_{av} = S P_g \tag{2.8}$$

and

$$P_{mech} = (1-S)\omega_s T_{av} = (1-S) P_g \tag{2.9}$$

2.2.1 Rotor Resistance Control:

Rotor resistance control [20] involves extracting some energy from the rotor and dissipating it as heat in a resistance so that the power converted into mechanical power is reduced. Thus for the same torque the motor operates at a reduced speed. Speed-torque and speed-rotor current characteristics of the wound-rotor induction motor, for various values of rotor resistance are shown in Fig. 2.1(a) and (b). According to eqn. (2.7) the maximum torque is independent of rotor resistance. However,

according to eqn. (2.6), the slip at which the maximum torque occurs depends upon the rotor resistance. As the rotor resistance is increased, the speed at which the maximum torque occurs decreases i.e. slip increases as shown in Fig. 2.1(a). According to eqn. (2.3) with increase in rotor resistance, the rotor current at a given slip decreases. Thus, with increase in rotor resistance, rotor current, and therefore, the stator current decreases giving higher torque to current ratio. Thus, in drives requiring low speed operation, larger output can be obtained from the machine, thus allowing better use of its capacity. Eqns. (2.5) and (2.3) show that, as the rotor resistance is increased for the same value of torque and rotor current, the machine operates at a lower speed. According to eqns. (2.8) and (2.9), this is achieved by reducing the power developed by the machine (P_{mech}) i.e. shaft power by increasing the power wasted in the rotor resistance. As a result of higher rotor copper loss, the efficiency of the motor is low. Since the copper loss mainly takes place in the external resistances connected to the rotor circuit, it does not cause over-heating of the machine; thus the motor is not derated. This type of speed control is possible only for slip-ring i.e. wound rotor induction motors. This method of speed control can only be adopted in a narrow speed range. Thus, we observe that the rotor resistance control is too inefficient for practical use except for momentary reduction of speed.

2.2.2 Injecting Voltage in the Rotor Circuit of Wound Rotor Induction Motor:

In this method, a certain fraction of rotor power extracted from the rotor circuit is fedback to the source, instead of being wasted in the resistance as in the case of rotor resistance control. Thus, lesser amount of power transferred to rotor through the air gap is converted into the mechanical power. Hence, for the same torque, machine operates at a lower speed. This scheme is called slip power recovery scheme. The schematic diagram of this scheme is shown in Fig. 2.2. Speed can also be controlled above the synchronous speed but the cost increases. Speed torque characteristic of the induction motor for this scheme is shown in Fig. 2.3. This scheme is used in high power application involving small speed variation below the synchronous speed, such as in high power fan and pump drives.

2.2.3 Variable Terminal Voltage Control:

This is a slip-control method [22] with constant frequency variable voltage being supplied to the motor stator. Obviously the voltage should only be reduced below the rated value. Speed-torque characteristics of the induction motor for variable values of stator voltage are shown in Fig. 2.4. Fig. 2.4(a) shows the characteristics for low slip induction motor, (motor with low rotor resistance) and Fig. 2.4(b) gives the characteristic for high slip induction motor, (motor with high rotor resistance). It can be seen that speed can be varied by a larger amount when the rotor resistance is high; however, this method can allow speed control only over a small range.

Eqns. (2.3) and (2.5) show that for a given slip, torque is proportional to square of stator voltage and the rotor current is proportional to stator voltage. As the stator voltage is reduced, torque to current ratio decreases. Consequently, for a given thermal loading on the machine, available torque decreases. Low speed operation without overheating is possible if the torque demand on the machine decreases as the speed decreases. Therefore, stator voltage control is suitable for the applications where speed is to be controlled in a limited range only and the load torque decreases with the speed.

Eqns. (2.8) and (2.9) show that with the decrease in speed, rotor copper loss increases but the power converted into mechanica power decreases. The stator voltage control is an inefficient method of speed control. This method of control is commonly used, inspite of poor efficiency and motor derating, because of lower cost compared to alternative methods of speed control such as variable frequency control and slip power recovery scheme.

2.2.4 Variable Frequency Control:

The synchronous speed of the induction motor can be controlled in a stepless way over a wide range by changing the supply frequency [19]. Change in supply frequency varies the synchronous speed, and therefore, speed of the motor. The resultant air-gap flux per pole is given by

$$\phi_r = \frac{1}{4.44\, K_w N_s} \left(\frac{V}{f} \right) \tag{2.10}$$

Therefore, in order to avoid saturation and excessive core-loss in stator and rotor cores which would cause sharp increase in magnetization current, the resultant air-gap flux ϕ_r and hence the flux density B_r must be kept constant as frequency is varied. To achieve this, it follows from eqn. (2.10), that, when frequency is varied, voltage must also be varied in such a way that the ratio of the motor terminal voltage and its frequency remains constant. Variable (V,f) supply from constant (V,f) supply can be arranged by the converter-inverter arrangement shown schematically in Fig. 2.5. Speed-torque characteristic for variable frequency control is shown in Fig. 2.6.

Motor speed can also be controlled above the rated speed by increasing the supply frequency above the rated frequency of the machine. Since the terminal voltage cannot be increased beyond the rated value, it is maintained constant at its rated value as the frequency is increased. Thus, speed control above the rated value is obtained with the reduction of the torque capability of the machine.

With variable frequency control, the regenerative braking can easily be obtained throughout its speed range by reducing the frequency in such a way that the synchronous speed at that frequency is lower than the actual motor speed.

Variable frequency control is a highly efficient method of speed control. Due to, high torque to current ratio, it provides fast acceleration and deceleration of the machine. A four quadrant drive can be realized using a variable frequency supply fed squirrel cage induction motor.

2.3 THE CONTROLLED SLIP STATIC INVERTER DRIVE:

The controlled slip static inverter drive [1] uses the versatile characteristic of the semiconductor inverter to achieve optimized control of a squirrel cage induction motor. This technique has been possible during the past few years due to the development of fast, powerful and efficient inverters.

Before any drive system can be applied effectively, the output quantities must be expressed in terms of the output quantities of the controller. These, in turn, must be realized from and related to the controller inputs. We shall now discuss the theory of this drive system.

2.3.1 Theory of Variable Speed Induction Motor Drive:

When balanced polyphase voltages are applied to the symmetric stator windings of an ac machine, a rotating magnetic field is created. A magnetized rotor placed in this field tends to spin in synchronism with this rotating field, thereby forming a synchronous motor. The speed of the motor is dependent on the speed of the field which in turn is a function of the

frequency of the applied voltage. As the frequency is changed to adjust the speed, it is necessary to maintain flux density near some optimum level. In an ac machine, the magnetic flux is related to voltage and frequency in the following manner:

$$\phi_s = \frac{KV}{\omega} \tag{2.11}$$

where K is a constant.

Thus, to control the action of an ac machine, the adjustment of voltage and frequency must be coordinated. If excitation losses and stator voltage drops are neglected, a balanced polyphase voltage $V \sin\omega t$, applied to the symmetric stator windings of a motor, produces a rotating magnetic field in the stator whose angular speed is given by eqn. (2.2) and whose magnitude by eqn. (2.11).

If the speed of the rotor is ω_r, then

$$\omega_{sl} = \omega_s - \omega_r \tag{2.12}$$

The voltage induced in the rotor is

$$V_r \sim \phi_s \, \omega_{sl} \tag{2.13}$$

The rotor being a closed circuit, the rotor current I_r will be,

$$I_r = \frac{V_r}{Z_r} = \frac{V_r}{\sqrt{r_r'^2 + (\omega_{sl} L_{lr}')^2}}$$

This, in turn produces a flux

$$\phi_r \sim I_r \sim \frac{\phi_s \omega_{sl}}{Z_r} \tag{2.14}$$

This flux lags stator flux ϕ_s by an angle

$$\theta = \frac{\pi}{2} + \tan^{-1}\left(\frac{\omega_{sl} L_{lr}'}{r_r'}\right) = \frac{\pi}{2} + \gamma \tag{2.15}$$

where,

$$\gamma = \tan^{-1} \frac{\omega_{sl} L_{lr}'}{r_r'} \tag{2.16}$$

The motor torque is given by

$$T = \phi_r \, \phi_s \sin\theta = \phi_r \, \phi_s \cos\gamma \tag{2.17}$$

Substituting the value of γ from eqn. (2.16) in eqn. (2.17) we get,

$$T \cong \phi_s^2 \frac{\omega_{sl} \, r_r'}{Z_r^{\,2}} \tag{2.18}$$

$$T \cong \left(\frac{V}{\omega}\right)^2 \frac{\omega_{sl} \, r_r'}{r_r'^2 + (\omega_{sl} L_{lr}')^2} \tag{2.19}$$

Thus, from eqn. (2.19), we observe that torque depends only on slip ω_{sl} and volts per cycle $\frac{V}{\omega}$.

Differentiating the expression for torque with respect to slip and setting it equal to zero yields

$$\omega_{sm} = \frac{r_r'}{L_{lr}'} \tag{2.20}$$

This is known as the breakdown slip speed associated with the breakdown point (corresponding to the breakdown i.e. maxm. torque).

Operating beyond breakdown slip yields high current, low power factors and high losses. If the slip is constrained and controlled to values below breakdown, high efficiency, high power factor and moderate currents result in an operation comparable to that of a dc machine. Further-more, this holds good even when the speed of the system is varied by adjusting the stator frequency provided that, as in any well designed machine, the flux is kept at a level high enough to obtain good performance, but low enough to control saturation and core losses. The direction of slip relative to the stator determines the direction of power flow, while the voltage determines the level of torque and hence, along with the frequency, the level of power flow.

Thus, eqn. (2.19) is a general expression defining torque involving the quantities of slip speed and excitation. Torque can be controlled by adjusting excitation, or slip, or both in combination. The choice of the particular mode of control depends on the load, the motor type and the controller. The ability to control slip and excitation precisely and accurately depends on the inverter which is used.

Forcing torques, which are a multiple of rated values, can be applied briefly by increasing excitation and/or slip. The resulting increase in losses can be tolerated because of the relatively large thermal time constant of the motor.

2.3.2 Control Technique:

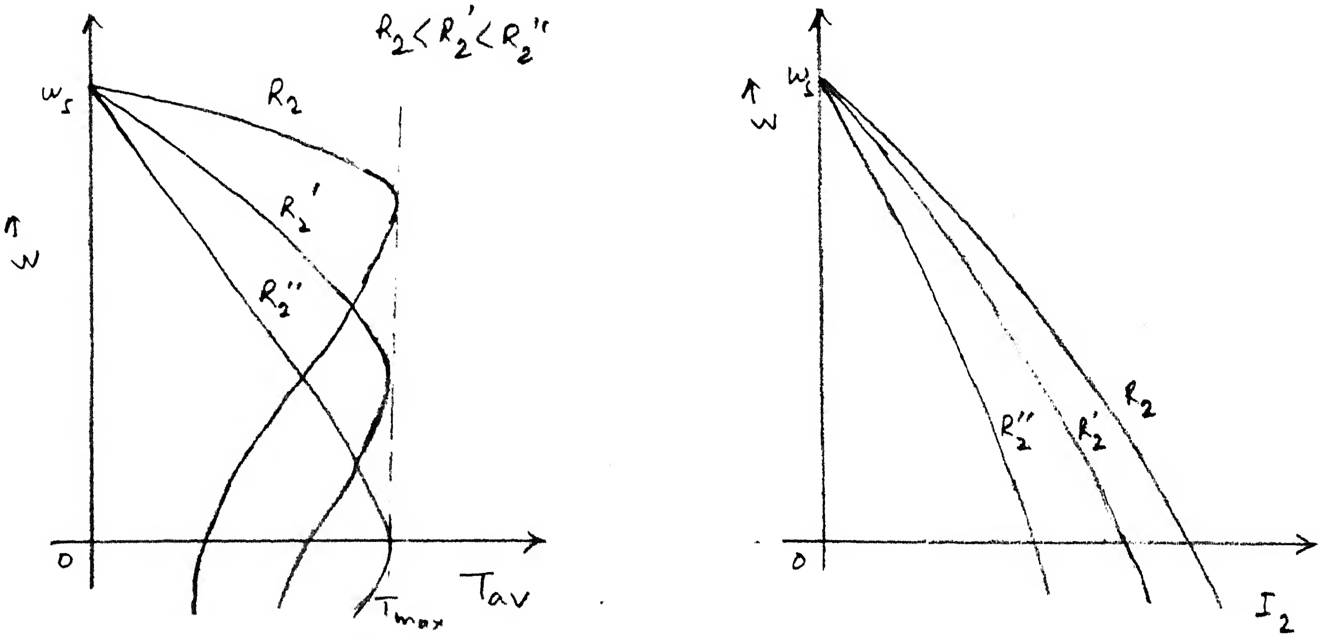
The application of dc drives is normally divided into two classical modes: the constant torque and constant horsepower ranges of operation. In both of the classical operating modes, the essence of the task is to adjust the levels of two interacting fluxes to control speed and torque. In the induction motor, the behaviour of stator flux is analogous to the field of a dc machine. In the constant torque range, stator flux can be maintained by controlling $\frac{V}{\omega}$ and current-slip factors. However, speed is a function of applied frequency and the flux or field 'weakening' is a consequence of operating above base frequency at a fixed voltage as the voltage cannot be increased beyond its rate of value.

Flux due to rotor currents is proportional to the product of stator flux and slip. It can be varied to set the torque by adjusting slip and/or excitation, just as the armature flux is controlled by adjusting current in a dc machine. To maintain the maximum value of rotor flux at some level, the slip must be increased as the stator flux is weakened in the constant horsepower mode. A representative control system is shown in Fig. 2.7 which includes a slip control loop and a stator flux regulation brought about by a shaped current reference that produces indirect stator flux control.

The constant stator flux method is not necessarily optimum, since, in the process of load forcing in the constant torque range, for a given current and speed, the torque is

proportional to the applied voltage squared. This implies that, the excess torque is a function of an excess stator flux at the same maximum rotor flux as measured by stator current. The high flux has the tendency to produce high magnetization losses in steady state in anticipation, so to speak, of the moment when it is necessary to produce brief forcing torque. However, slip losses appear only when the load is being driven.

On the other hand, the essence of harmonics in the waveform, while not affecting increased magnetization losses, does induce rotor losses because their relative slip is high and is virtually uneffected by the speed and loading of the machine. Hence, their contribution to motor loss is roughly proportional to the square of the stator flux. Such losses would soar under conditions of over-excitation. Thus, in the constant torque range, an optimized system can operate with a fixed value of slip. Torque is controlled by adjusting the level of stator flux. Such a system calling for a variable stator flux can also be obtained by forcing that flux with a shaped voltage or flux reference since $T \sim (\frac{V}{\omega})^2 S$, $\frac{I^2}{S}$, $\phi_s{}^2 S$. We will use independent current/speed and/or slip control to study the improvement in the stability of the drive.



(a) Speed-torque curve (b) Speed-rotor current curve

Fig. 2.1 Performance curves of Induction motor for different values of rotor resistance.

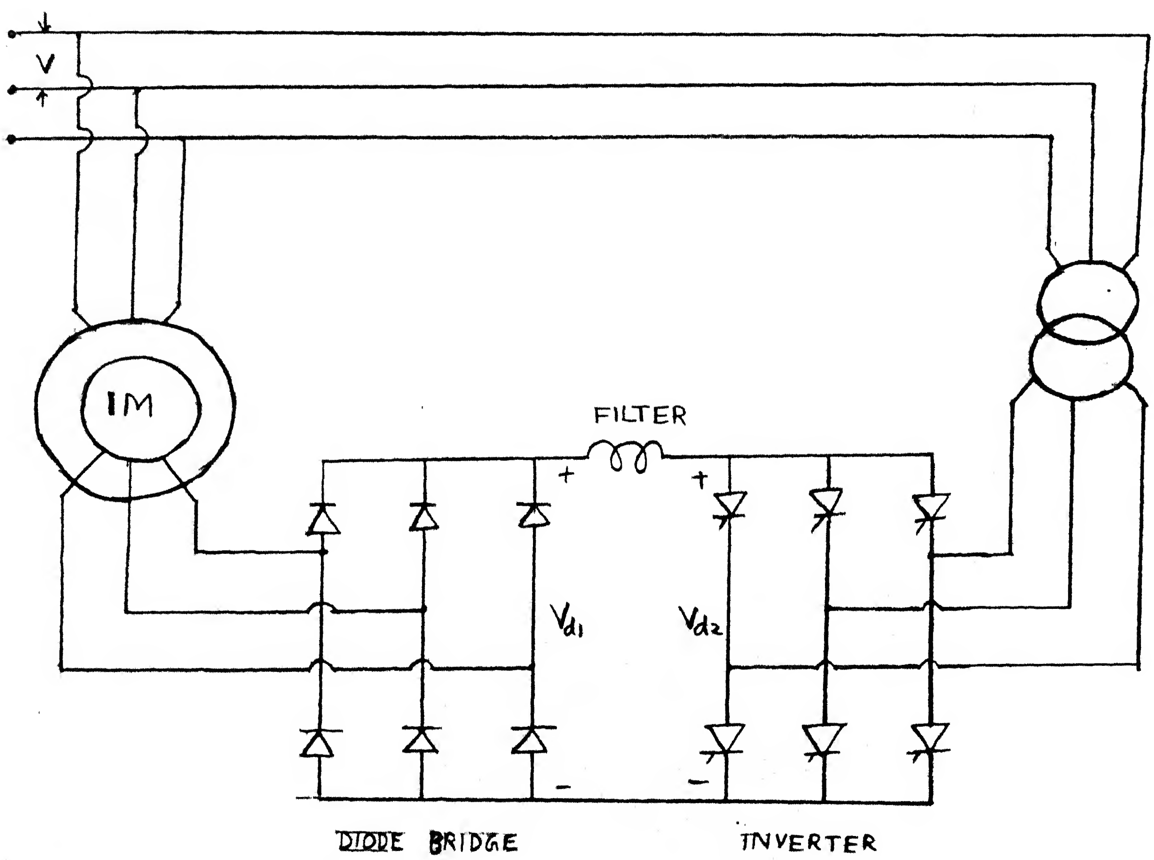


Fig. 2.2 Slip power recovery scheme for speed control of induction motor below synchronous speed.

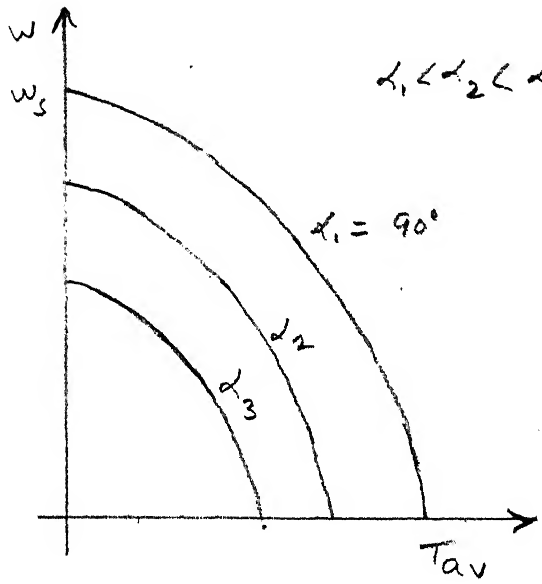
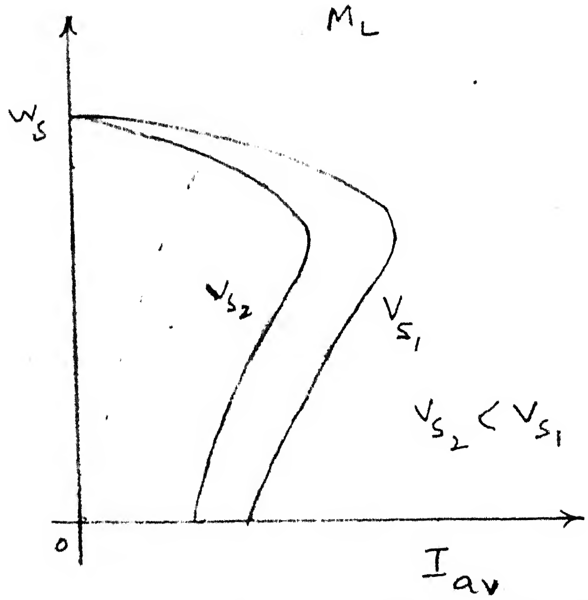
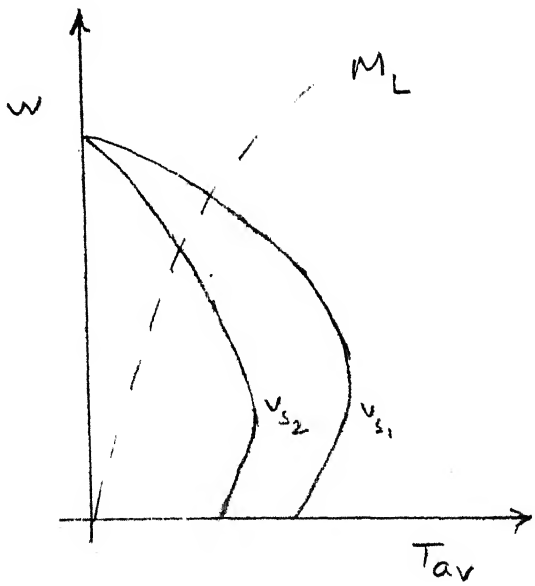


Fig. 2.3 Speed-torque characteristic of induction motor with slip power recovery control.



(a) Low slip induction motor



(b) High slip induction motor

Fig. 2.4 Stator voltage control of induction motor

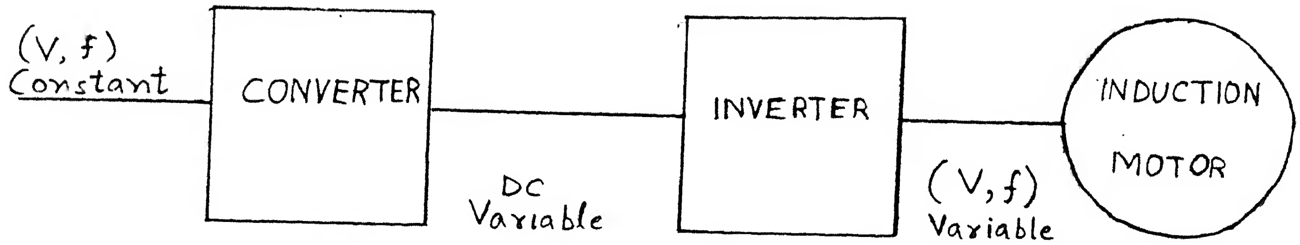


Fig. 2.5 Scheme for variable frequency control of induction motor

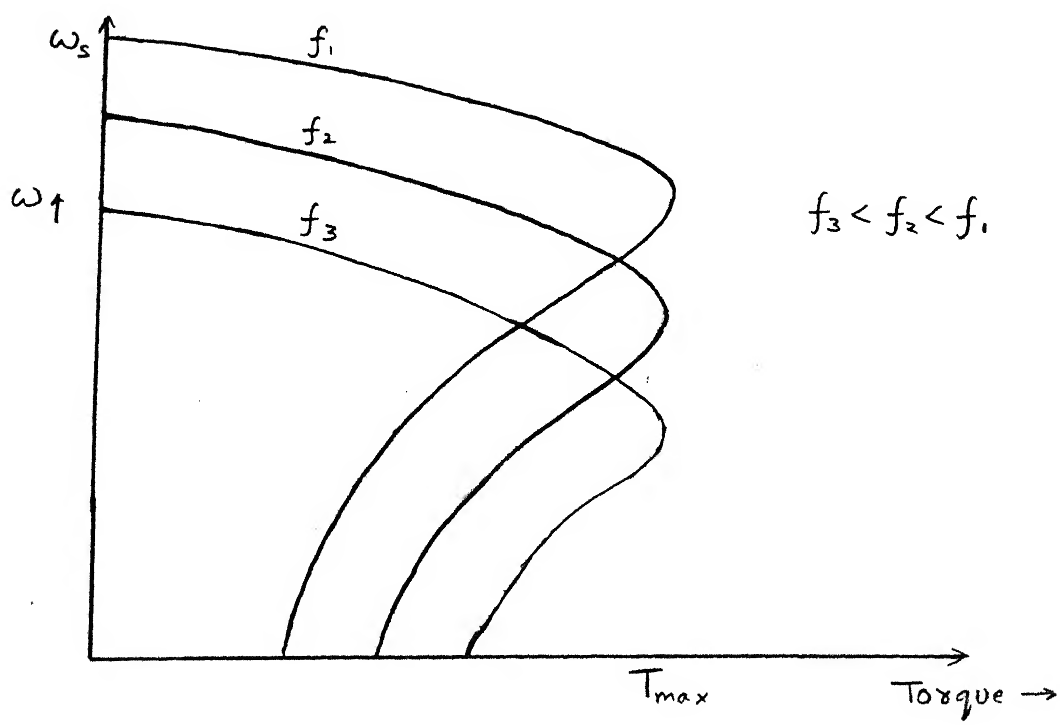


Fig. 2.6 Speed torque characteristics of induction motor for various values of frequencies, f_1 is the rated frequency.

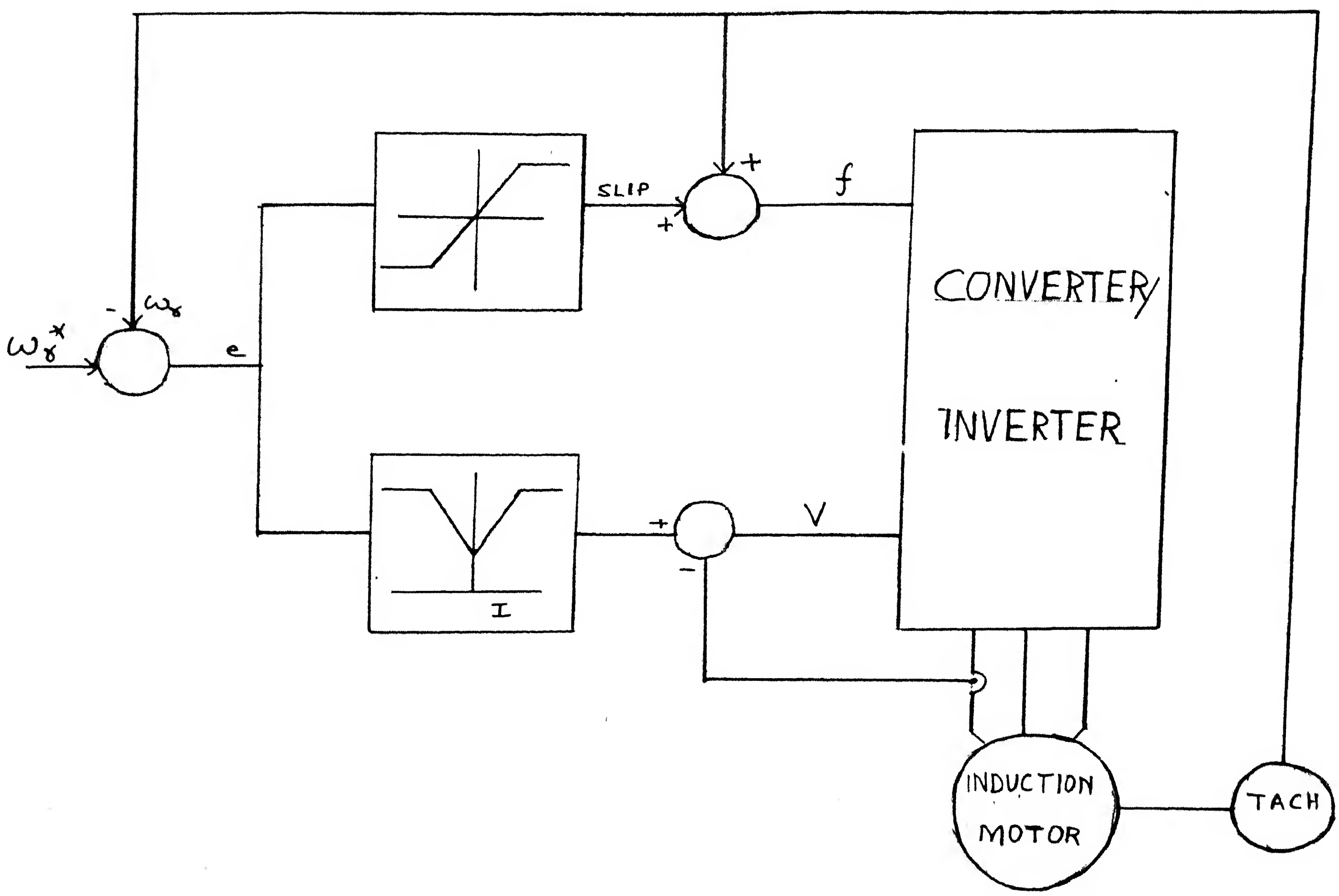


Fig. 2.7 Controlled slip drive system

CHAPTER 3

MATHEMATICAL MODELLING OF INDUCTION MOTOR DRIVE

3.1 INTRODUCTION:

Computer simulation is widely used to study the behaviour of physical systems under various conditions. Appropriate system models are required for digital simulation. In the previous chapter, we described the theory and control technique of variable frequency variable speed induction motor drive. We will now describe the drive configuration in detail. In this chapter, we will develop a suitable model of the induction motor for use in the variable frequency variable speed drive. A complete model of the drive which includes models of the induction motor, converter and inverter has been developed by making suitable assumptions. For the purpose of analysis, we have neglected saturation effects in the motor.

3.2 DESCRIPTION OF THE DRIVE:

Normally an industrial drive draws its power from the standard three-phase system of constant voltage magnitude and fixed frequency. The first requirement is to convert this to dc, the usual instrument for this purpose being the six thyristor bridge rectifier. The dc power is then converted by an inverter to ac power at variable voltage and frequency for application to the motor.

The output voltage of the rectifier has considerable harmonic content, the harmonic frequencies being multiples of six times the supply frequency. The input current to the inverter has also substantial harmonic content, the harmonic frequencies being multiples of six times the inverter output frequency. These two sets of harmonics must be isolated from one another by a filter interposed between the rectifier and the inverter. A simplified diagram of the drive considered is given in Fig. 3.1. We will now describe components of the drive [9].

3.2.1 Converter:

The converter is almost invariably a six thyristor bridge as depicted in Fig. 3.2. This gives six pulse operation, i.e., the output voltage and input current waveforms correspond to six phase operation. The converter of Fig. 3.2 may be directly connected to the three-phase supply or a transformer may be interposed. Direct connection has the merits of lower cost, lower weight and volume (i.e. lesser space) and higher efficiency. Its disadvantages are that, the maximum dc output voltage is dictated by the ac supply voltage and no part of the drive is grounded, the ground being that of the ac supply.

The dc output voltage available from the bridge is given by,

$$V_R = \frac{3\sqrt{3}}{\pi} V_s \cos\alpha \tag{3.1}$$

The voltage level can be varied very rapidly, as far as a drive is concerned almost instantaneously, between the positive and negative maxima by controlling the instants at which the thyristors are switched to the conducting mode. The thyristor converter is a convenient power source for a drive, its major disadvantages being harmonics on both the output and input sides and poor power factor at reduced output voltage.

3.2.2 The Filter:

High efficiency is essential when handling large power so that the only components considered for the filter are capacitors and inductors. Depending on the inverter, the filter may be a large capacitor, an LC low pass combination or an inductor. The so-called current source inverters require an inductor to reduce the current ripple caused by the rectifier harmonics. This is a substantial component with about ten times the inductance of the load. The controlled rectifier bridge and filter together form a dc current source which supplies constant regulated dc current to the inverter.

3.2.3 The Inverter:

The inverter shown in Fig. 3.3 is the autosequential commutated inverter [4]. This is extremely robust and trouble free device which works in the complementary commutation mode, i.e. the incoming thyristor turns off the outgoing thyristor. In Fig. 3.3, thyristors T_1-T_6 switch the load current at a rate

established by the inverter control and establish the inverter output frequency. Capacitors C_1-C_6 provide the necessary commutation energy while diodes D_1-D_6 isolate the capacitors from the load. Ideally, only two phases conduct at any instant of time resulting in six modes of operation.

A diagram illustrating the thyristor gating sequence and resulting line currents is shown in Fig. 3.4. The dc input current is divided among the load phases by the inverter so that the current in each phase has the rectangular waveform.

If I_R is the magnitude of the current in the link, these stepped currents exciting the three stator phases can be represented by the Fourier expansion given by [25],

$$i_{as} = \frac{2\sqrt{3}I_R}{\pi}[\cos \omega_e t - \frac{1}{5} \cos 5\omega_e t + \frac{1}{7} \cos 7\omega_e t - \ldots] \tag{3.2}$$

$$i_{bs} = \frac{2\sqrt{3}I_R}{\pi}[\cos(\omega_e t - \frac{2\pi}{3}) - \frac{1}{5} \cos(5\omega_e t + \frac{2\pi}{3}) + \frac{1}{7}\cos(7\omega_e t - \frac{2\pi}{3}) \ldots] \tag{3.3}$$

$$i_{cs} = \frac{2\sqrt{3}I_R}{\pi}[\cos(\omega_e t + \frac{2\pi}{3}) - \frac{1}{5} \cos(5\omega_e t - \frac{2\pi}{3}) + \frac{1}{7}\cos(7\omega_e t + \frac{2\pi}{3}) \ldots] \tag{3.4}$$

The combination of current source inverter and controlled rectifier readily handles reversal of power flow as from a generating load.

3.3 MODELLING OF THE DRIVE:

The following assumptions are made for the purpose of developing the model of the induction motor drive:

i) The voltages, currents and impedances are assumed to be symmetric and balanced;

ii) Commutation overlap is neglected. Switching is considered to be instantaneous and no voltage drop occuring in the thyristors.

iii) The induction machine is considered to be an ideal symmetric machine in which the stator and the rotor windings are distributed uniformly so as to produce a sinusoidal space distribution of MMF in the air gap.

iv) Saturation of magnetic core in the induction machine is neglected.

v) Core losses in induction machine are neglected.

vi) All parameters of the machine are assumed to be constant.

vii) The motor is assumed to be a wye-connected three-phase, three-wire system.

Generally, these assumptions do not indicate serious restrictions while they certainly simplify the model. Neglecting harmonics produced by the inverter power supply does not

reduce the significance of the results in terms of stability and transient response. This simplifies the model and enables faster computation of dynamic performance.

3.3.1 Mathematical Model of the Induction Motor for Controlled Current Operation:

When a stator winding is distributed for the purpose of producing a sinusoidal MMF wave in space, it is convenient to portray the winding as an equivalent single coil and express the mutual coupling between it and an equivalent rotor coil as a sinusoidal function of the angular displacement between their magnetic axes. If the induction motor has either a squirrel-cage rotor or a coil wound rotor with the same number of phases (and poles) as the stator, the rotor can be considered as having equivalent coils. The stator windings are identical to each other. Similarly the rotor windings are identical to each other. The line to neutral stator and rotor voltage equations are:

$$[V] = [R]\,[I] + p[\lambda] \tag{3.5}$$

where,

$$[\lambda]^t = [\lambda_{as}\ \lambda_{bs}\ \lambda_{cs}\ \lambda_{ar}\ \lambda_{br}\ \lambda_{cr}] \tag{3.6}$$

$$[I]^t = [i_{as}\ i_{bs}\ i_{cs}\ i_{ar}\ i_{br}\ i_{cr}] \tag{3.7}$$

$$[V]^t = [v_{as}\ v_{bs}\ v_{cs}\ v_{ar}\ v_{br}\ v_{cr}] \qquad (3.8]$$

$$[R] = \begin{bmatrix} r_s & 0 & 0 & 0 & 0 & 0 \\ 0 & r_s & 0 & 0 & 0 & 0 \\ 0 & 0 & r_s & 0 & 0 & 0 \\ 0 & 0 & 0 & r_r' & 0 & 0 \\ 0 & 0 & 0 & 0 & r_r' & 0 \\ 0 & 0 & 0 & 0 & 0 & r_r' \end{bmatrix} \tag{3.9}$$

and p denotes the 'd/dt' operator.

Since, the stator and the rotor windings are 3-phase wire systems, the flux linkage equations [8] are,

$$[\lambda] = [L]\,[I] \tag{3.10}$$

where,

$$[L]= \begin{bmatrix} L_{ss} & 0 & 0 & L_{sr}\cos\theta_r & L_{sr}\cos(\theta_r+\frac{2\pi}{3}) & L_{sr}\cos(\theta_r-\frac{2\pi}{3}) \\ 0 & L_{ss} & 0 & L_{sr}\cos(\theta_r-\frac{2\pi}{3}) & L_{sr}\cos\theta_r & L_{sr}\cos(\theta_r+\frac{2\pi}{3}) \\ 0 & 0 & L_{ss} & L_{sr}\cos(\theta_r+\frac{2\pi}{3}) & L_{sr}\cos(\theta_r-\frac{2\pi}{3}) & L_{sr}\cos\theta_r \\ L_{sr}\cos\theta_r & L_{sr}\cos(\theta_r-\frac{2\pi}{3}) & L_{sr}\cos(\theta_r+\frac{2\pi}{3}) & L_{rr} & 0 & 0 \\ L_{sr}\cos(\theta_r+\frac{2\pi}{3}) & L_{sr}\cos\theta_r & L_{sr}\cos(\theta_r-\frac{2\pi}{3}) & 0 & L_{rr} & 0 \\ L_{sr}\cos(\theta_r-\frac{2\pi}{3}) & L_{sr}\cos(\theta_r+\frac{2\pi}{3}) & L_{sr}\cos\theta_r & 0 & 0 & L_{rr} \end{bmatrix} \tag{3.11}$$

where,

$$L_{ss} = L_s - L_{sm} \tag{3.12}$$

$$L_{rr} = L_r' - L_{rm} \tag{3.13}$$

Due to the sinusoidal space variation of the mutual inductances with respect to the displacement angle θ_r, time - varying coefficients will appear in the voltage equations. This undesirable feature can be eliminated by a proper change of variables which, in effect, transforms the phasor voltages and currents of both the stator and rotor to a common frame of reference.

Fig. 3.5 shows the angular relation of the stator and rotor magnetic axes of a three-phase machine with the third set which is an orthogonal set (d-q axis) rotating at an arbitrary electrical angular speed ω ($= \frac{d\theta}{dt}$). It is clear that as-bs-cs set is fixed in the stator and ar-br-cr set is fixed in the rotor and hence rotates at an angular velocity of ω_r. The angular relationship between the three sets of axes at time t=0, can be selected arbitrarily. However, it is convenient to assume that at time t=0, the q axis and the magnetic axes of the stator (as) and rotor (ar) phases coincide [21].

The following power invariant Park's transformation [21], which can be developed based upon symmetries inherent in the machine and using mathematical theory of groups, is considered.

$$T_s = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \tag{3.14}$$

Also,

$$T_R = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\beta & \sin\beta & 1 \\ \cos(\beta - \frac{2\pi}{3}) & \sin(\beta - \frac{2\pi}{3}) & 1 \\ \cos(\beta + \frac{2\pi}{3}) & \sin(\beta + \frac{2\pi}{3}) & 1 \end{bmatrix} \tag{3.15}$$

Then, the transformed equations for the balanced system, which can be correlated to the angular relation of the axes as shown in Fig. 3.5, are as follows,

$$\begin{bmatrix} f_{qs} \\ f_{ds} \\ f_{os} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2}\cos\theta & \sqrt{2}\cos(\theta - \frac{2\pi}{3}) & \sqrt{2}\cos(\theta + \frac{2\pi}{3}) \\ \sqrt{2}\sin\theta & \sqrt{2}\sin(\theta - \frac{2\pi}{3}) & \sqrt{2}\sin(\theta + \frac{2\pi}{3}) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \end{bmatrix} \tag{3.16}$$

and for rotor,

$$\begin{bmatrix} f_{qr} \\ f_{dr} \\ f_{or} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2}\cos\beta & \sqrt{2}\cos(\beta - \frac{2\pi}{3}) & \sqrt{2}\cos(\beta + \frac{2\pi}{3}) \\ \sqrt{2}\sin\beta & \sqrt{2}\sin(\beta - \frac{2\pi}{3}) & \sqrt{2}\sin(\beta + \frac{2\pi}{3}) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} f_{ar} \\ f_{br} \\ f_{cr} \end{bmatrix} \tag{3.17}$$

where $\beta = \theta - \theta_r$. (3.18)

In these equations, variable f represents either voltage, current or flux linkage. These equations are restricted by the condition that the instantaneous angular displacement θ of the arbitrary reference frame must be a continuous time function.

f_{os} and f_{or} are taken because, in general, three indepe-ndent variables are necessary. If, however, only balanced conditions are to be considered, the third voltage or current can be defined in terms of other two. Hence, a third variable is unnecessary.

Also, if a 3-wire system are analysed, it can be shown that for the balanced system the zero subscripts (f_{os} and f_{or}) are non-existent. So these quantities can be excluded from its equivalent circuit development.

The equation (3.10) can be written as,

$$\begin{bmatrix} \lambda_S \\ \lambda_R \end{bmatrix} = \begin{bmatrix} L_{SS} & L_{SR} \\ L_{SR}^t & L_{RR} \end{bmatrix} \begin{bmatrix} i_S \\ i_R \end{bmatrix} \tag{3.19}$$

where, S refers to stator quantities and R refers to rotor quantities. L_{SR}^{t} is the transpose of L_{SR}. Using the transformations,

$$[\lambda] = [T]\,[\lambda_{park}] \tag{3.20}$$

and

$$[i] = [T]\,[i_{park}] \tag{3.21}$$

which define λ_{park} and i_{park}, Equation (3.19) is transformed [23] to,

$$\begin{bmatrix} \lambda_{S\,(park)} \\ \lambda_{R\,(park)} \end{bmatrix} = \begin{bmatrix} T_S^{-1} & 0 \\ 0 & T_R^{-1} \end{bmatrix} \begin{bmatrix} L_{SS} & L_{SR} \\ L_{SR}^{t} & L_{RR} \end{bmatrix} \begin{bmatrix} T_S & 0 \\ 0 & T_R \end{bmatrix} \begin{bmatrix} i_{S(park)} \\ i_{R(park)} \end{bmatrix}$$

$$= \begin{bmatrix} T_S^{-1} L_{SS}\, T_S & T_S^{-1} L_{SR} T_R \\ T_R^{-1} L_{SR}^{t} T_S & T_R^{-1} L_{RR} T_R \end{bmatrix} \begin{bmatrix} i_{S(park)} \\ i_{R(park)} \end{bmatrix} \tag{3.22}$$

Finally equation (3.22) reduces to,

$$\begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_{os} \\ \lambda_{qr} \\ \lambda_{dr} \\ \lambda_{or} \end{bmatrix} = \begin{bmatrix} L_{ss} & 0 & 0 & \frac{3}{2}L_{sr} & 0 & 0 \\ 0 & L_{ss} & 0 & 0 & \frac{3}{2}L_{sr} & 0 \\ 0 & 0 & L_{ss} & 0 & 0 & 0 \\ \frac{3}{2}L_{sr} & 0 & 0 & L_{rr} & 0 & 0 \\ 0 & \frac{3}{2}L_{sr} & 0 & 0 & L_{rr} & 0 \\ 0 & 0 & 0 & 0 & 0 & L_{rr} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{os} \\ i_{qr} \\ i_{dr} \\ i_{or} \end{bmatrix} \tag{3.23}$$

Premultiplying both sides of voltage equation (3.5) by T^{-1}, we have

$$T^{-1}\,[V] = T^{-1}[R]\,[I] + T^{-1}\,p[\lambda] \tag{3.24}$$

Thus we obtain, in terms of transformed variables,

$$[V_{park}] = [R]\,[I_{park}] + T^{-1}\,[p(T[\lambda_{park}])] \tag{3.25}$$

$$[V_{park}] = [R][I_{park}]+T^{-1}(T_p[\lambda_{park}]+(pT)[\lambda_{park}]) \tag{3.26}$$

or

$$[V_{park}] = [R]\,[I_{park}] + p[\lambda_{park}] + T^{-1}\,pT[\lambda_{park}) \tag{3.27}$$

Assuming balanced condition (i.e. zero sequence current is zero, and consequently, zero sequence voltage is also zero), and using equation (3.27) for stator and rotor voltages, we get the voltage equation as,

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v'_{qr} \\ v'_{dr} \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 & 0 \\ 0 & r_s & 0 & 0 \\ 0 & 0 & r'_r & 0 \\ 0 & 0 & 0 & r'_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i'_{qr} \\ i'_{dr} \end{bmatrix} + p \begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda'_{qr} \\ \lambda_{dr} \end{bmatrix} + \begin{bmatrix} \lambda_{ds} & 0 \\ -\lambda_{qs} & 0 \\ 0 & \lambda'_{dr} \\ 0 & \lambda'_{qr} \end{bmatrix} p \begin{bmatrix} \theta \\ \beta \end{bmatrix} \tag{3.28}$$

where,

$$\lambda_{qs} = L_{ls}\,i_{qs} + M\,(i_{qs} + i'_{qr})$$

$$\lambda_{dr} = L_{ls}i_{ds} + M\,(i_{ds} + i'_{dr})$$

$$\lambda'_{qr} = L'_{lr}\, i'_{qr} + M(i_{qs} + i'_{qr})$$

$$\lambda'_{dr} = L'_{lr}\, i'_{dr} + M(i_{ds} + i'_{dr}) \qquad (3.29)$$

and,

$$L_{ls} = L_{ss} - \frac{3}{2} L_{ms}$$

$$L'_{lr} = L'_{rr} - \frac{3}{2} L_{ms}$$

$$M = \frac{3}{2} L_{ms}$$

$$L_{ms} = \frac{N_s}{N_r} L_{sr} \qquad (3.30)$$

prime denote rotor quantities referred to the stator side.

Expression for instantaneous electromagnetic torque can be obtained by applying the principle of virtual displacement based upon the concept of virtual work. This relation, which is positive for motor action, is,

$$T_e = \left(\frac{n}{2}\right) \left(\frac{P}{2}\right) M\, (i_{qs}\, i'_{dr} - i_{ds}\, i'_{qr}) \qquad (3.31)$$

Using eqns. (3.23), (3.28), (3.29), (3.30) and putting $v'_{qr} = v'_{dr} = 0$, we get induction machine equations [2] in the matrix form as shown below:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s+pL_s & \omega L_s & pM & \omega M \\ -\omega L_s & r_s+pL_s & -\omega M & pM \\ pM & (\omega-\omega_r)M & r'_r+pL'_r & (\omega-\omega_r)L'_r \\ -(\omega-\omega_r)M & pM & -(\omega-\omega_r)L'_r & r'_r+pL'_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i'_{qr} \\ i'_{dr} \end{bmatrix} \qquad (3.32)$$

Here, $L_s = L_{ls} + M$

and $\quad L_r' = L_{lr}' + M \qquad (3.33)$

For synchronously rotating reference frame $\omega = \omega_e$, hence the equation (3.29) becomes

$$\begin{bmatrix} v_{qs}^e \\ v_{ds}^e \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s+pL_s & \omega_e L_s & pM & \omega_e M \\ -\omega_e L_s & r_s+pL_s & -\omega_e M & pM \\ pM & \omega_{sl} M & r_r'+pL_r' & \omega_{sl} L_r' \\ -\omega_{sl} M & pM & -\omega_{sl} L_r' & r_r'+pL_r' \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ i_{ds}^e \\ i_{qr}'^e \\ i_{dr}'^e \end{bmatrix} \qquad (3.34)$$

where, $\omega_{sl} = \omega_e - \omega_r$

or $\quad \omega_{sl} = \omega_e S \qquad (3.35)$

The electromagnetic torque for three phase machine is,

$$T_e = \frac{3}{2}\,\frac{P}{2}\,M(i_{qs}^e\ i_{dr}'^e - i_{ds}^e\ i_{qr}'^e) = T_L + \frac{2J}{P}(p\omega_r) \qquad (3.36)$$

The 3/2 term which appears in the above expression is the result of using a transformation of variables which preserves the input power from phase to d-q quantities.

Using Equation (3.4) and applying the proper equations of transformation (Appendix I), we obtain the corresponding q- and d-axis currents in the synchronously rotating reference frame as shown,

$$i_{qs}^{e} = \frac{2\sqrt{3}}{\pi} I_R \left(1 - \frac{2}{35}\cos 6\omega_e t - \frac{2}{143}\cos 12\omega_e t - \ldots\right) \qquad (3.37)$$

$$i_{ds}^{e} = \frac{2\sqrt{3}}{\pi} I_R \left(- \frac{12}{35}\sin 6\omega_e t - \frac{24}{143}\sin 12\omega_e t - \ldots \right) \qquad (3.38)$$

For convenience, these currents can be expressed [6] as,

$$i_{qs}^{e} = I_R' \, g_{qs}^{e} \qquad (3.39)$$

$$i_{ds}^{e} = I_R' \, g_{ds}^{e} \qquad (3.40)$$

where,

$$g_{qs}^{e} = 1 - \frac{2}{35}\cos 6\omega_e t - \frac{2}{143}\cos 12\omega_e t - \ldots \qquad (3.41)$$

$$g_{ds}^{e} = - \frac{12}{35}\sin 6\omega_e t - \frac{24}{143}\sin 12\omega_e t - \ldots \qquad (3.42)$$

and,

$$I_R' = \frac{2\sqrt{3}}{\pi} I_R \qquad (3.43)$$

Assuming no power loss in the inverter, the power into and out of the inverter is identical, so that we get,

$$V_I I_R = \frac{3}{2}\left(v_{qs}^{e}\, i_{qs}^{e} + v_{ds}^{e}\, i_{ds}^{e}\right) \qquad (3.44)$$

The inverter voltage is obtained by combining eqns. (3.39), (3.40) and (3.44) as,

$$V_I = \frac{3\sqrt{3}}{\pi}\left(v_{qs}^{e}\, g_{qs}^{e} + v_{ds}^{e}\, g_{ds}^{e}\right) \qquad (3.45)$$

or,

$$V_I' = v_{qs}^e \, g_{qs}^e + v_{ds}^e \, g_{ds}^e \quad (3.46)$$

where,

$$V_I' = \frac{\pi}{3\sqrt{3}} V_I \quad (3.47)$$

Assuming continuous current in the smoothing reactor, the quantities I_R' and V_I' can be viewed as normalized dc link variables referred to the d-q axes.

The differential equation expressing the dc link variables is expressed in terms of normalized quantities [6] as,

$$V_R' = V_I' + (R_F' + pL_F')I_R' \quad (3.48)$$

where,

$$R_F' = \frac{\pi^2}{18} R_F \quad (3.49)$$

$$L_F' = \frac{\pi^2}{18} L_F \quad (3.50)$$

and,

$$V_R' = \frac{\pi}{3\sqrt{3}} V_R \quad (3.51)$$

Using equations (3.34), (3.39), (3.40), (3.46) and (3.48), we obtain the d-q equivalent circuit of a current controlled induction motor drive in the synchronously rotating reference frame as shown in Fig. 3.6.

Although, the actual system operates with rectangular wave excitation from a high equivalent impedance source, it is

well known that the machine stability is determined primarily by the fundamental components of machine variables. If the effects of harmonics is neglected, then, we have,

$$g_{qs}^{e} \cong 1.0 \tag{3.52}$$

$$g_{ds}^{e} \cong 0, \tag{3.53}$$

whereby, from eqn. (3.39) and eqn. (3.40)

$$i_{qs}^{e} = I_R' \tag{3.54}$$

$$i_{ds}^{e} = 0. \tag{3.55}$$

Thus, we observe that the current in the stator q-axis, I_R', corresponds to the peak value of the fundamental component of motor phase current. The d-axis stator current is identically zero during both steady-state and transient conditions due to the positioning of the synchronously rotating reference frame axes.

Also, equation (3.46) reduces to

$$V_I' = v_{qs}^{e} \tag{3.56}$$

with v_{ds} assuming the open-circuit value resulting from mutual coupling.

By neglecting harmonics, the detailed equivalent circuit of Fig. 3.6 reduces to the simplified equivalent circuit shown in Fig. 3.7.

Combining equations (3.54) and (3.55) with the equations of the induction machine in the synchronously rotating reference frame, we get the drive equations as

$$\begin{bmatrix} V_R' \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s+R_F'+p(L_S+L_F') & pM & \omega_e M \\ pM & r_r'+pL_r' & \omega_{sl}L_r' \\ -\omega_{sl}M & -\omega_{sl}L_r' & r_r'+pL_r' \end{bmatrix} \begin{bmatrix} i_{qs}^e \\ i_{qr}'^e \\ i_{dr}'^e \end{bmatrix} \tag{3.57}$$

and,

$$T_e = \frac{3P}{4\omega_b} M i_{qs}^e \, i_{dr}'^e = T_L + \frac{2J}{P} p\omega_r \tag{3.58}$$

We will use the non-linear eqns. (3.57) and (3.58) to develop the linearized model of the drive in the next chapter.

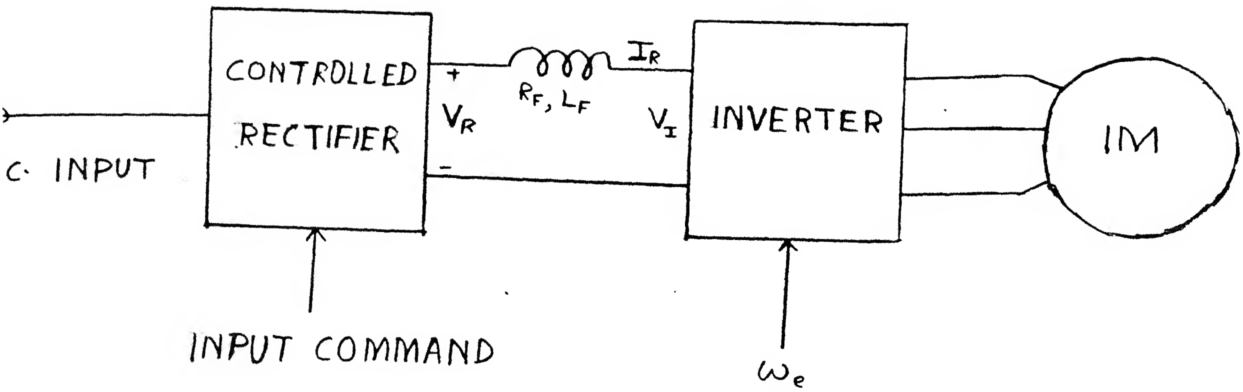


Fig. 3.1 Basic controlled current source inverter induction motor drive.

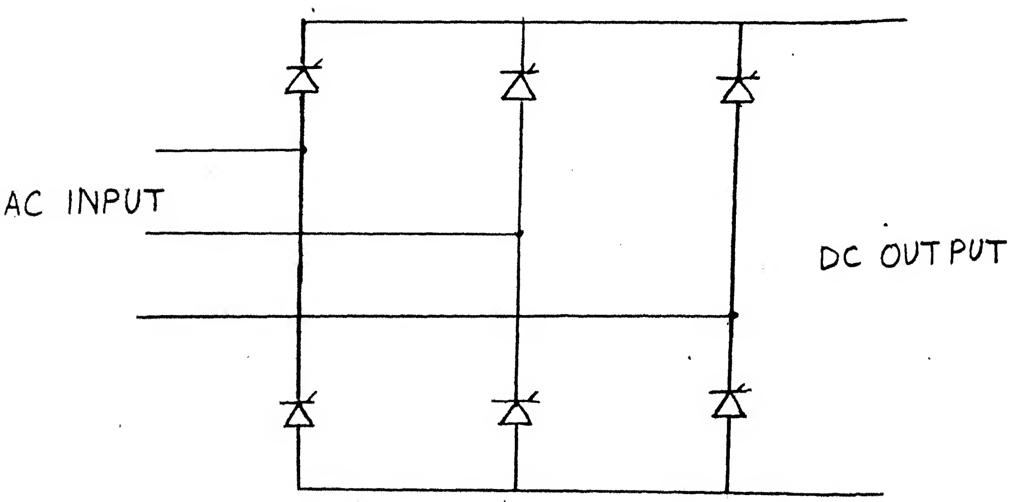


Fig. 3.2 A three-phase fully controlled rectifier

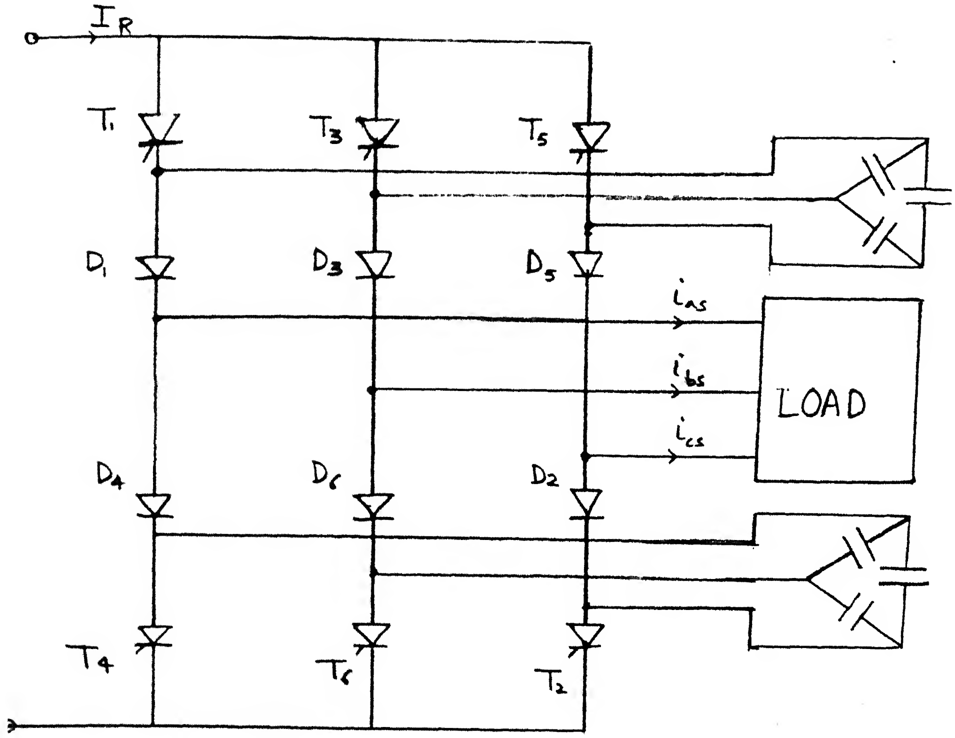


Fig. 3.3 An autosequential current source inverter

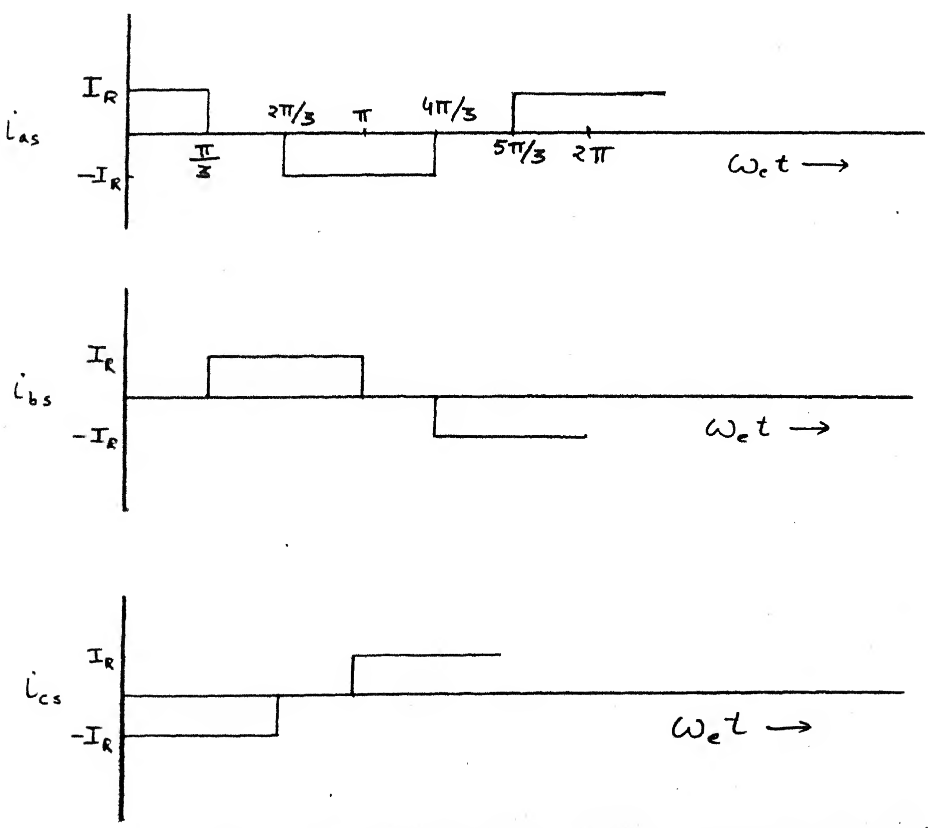


Fig. 3.4 Inverter gating sequence and resulting line currents.

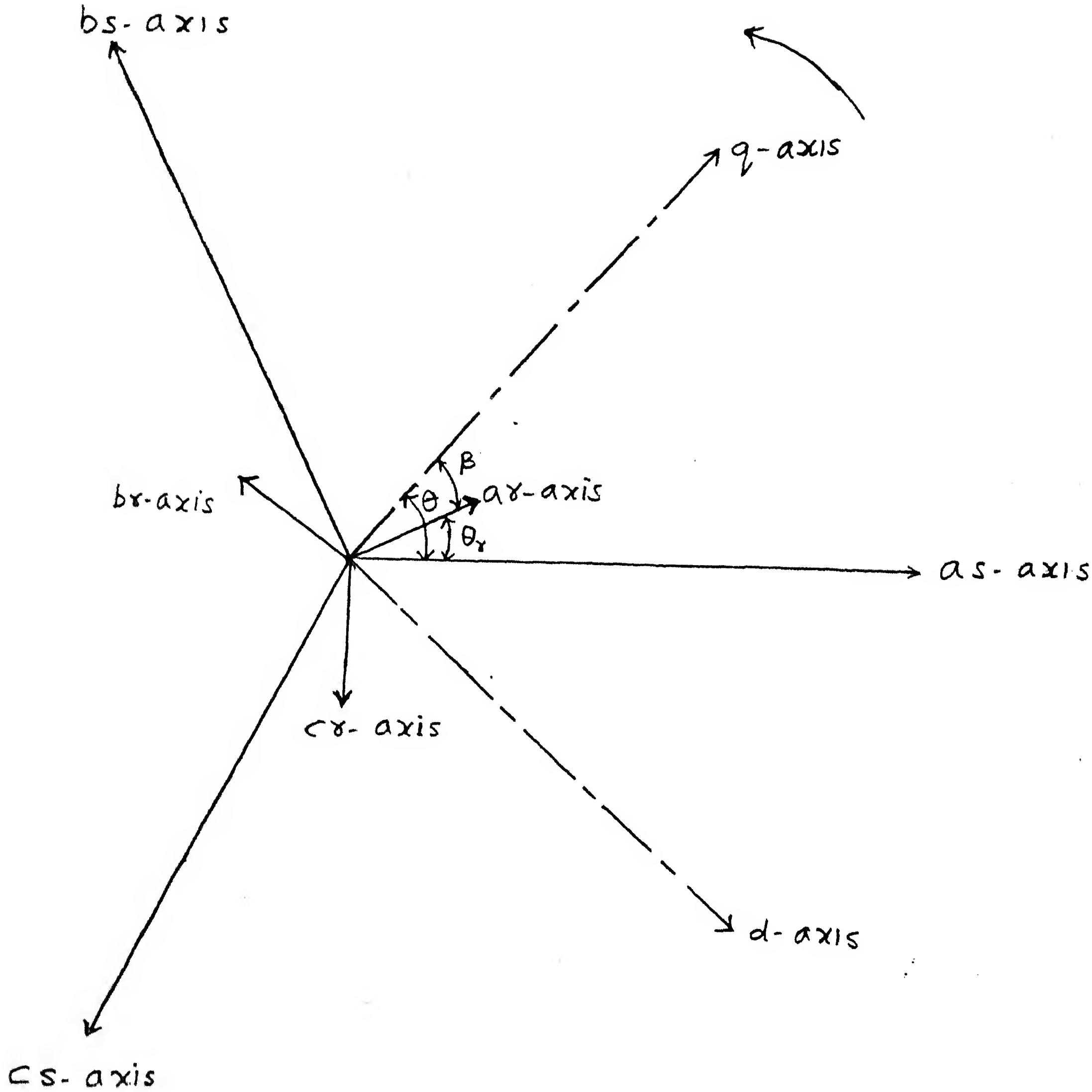


Fig. 3.5 Angular relation of stator and rotor axis with d-q axis.

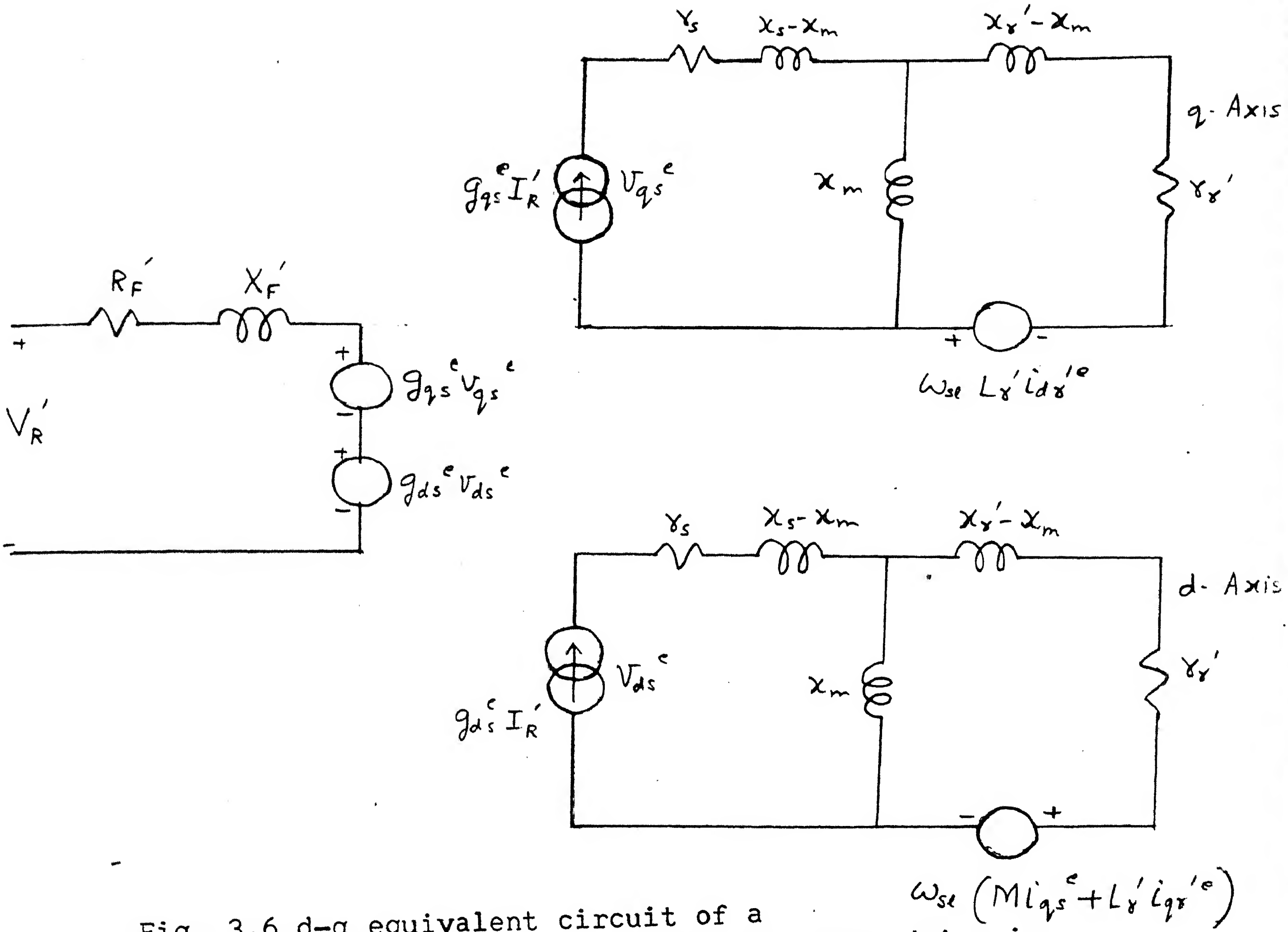


Fig. 3.6 d-q equivalent circuit of a controlled current induction motor drive in the synchronously rotatint reference frame.

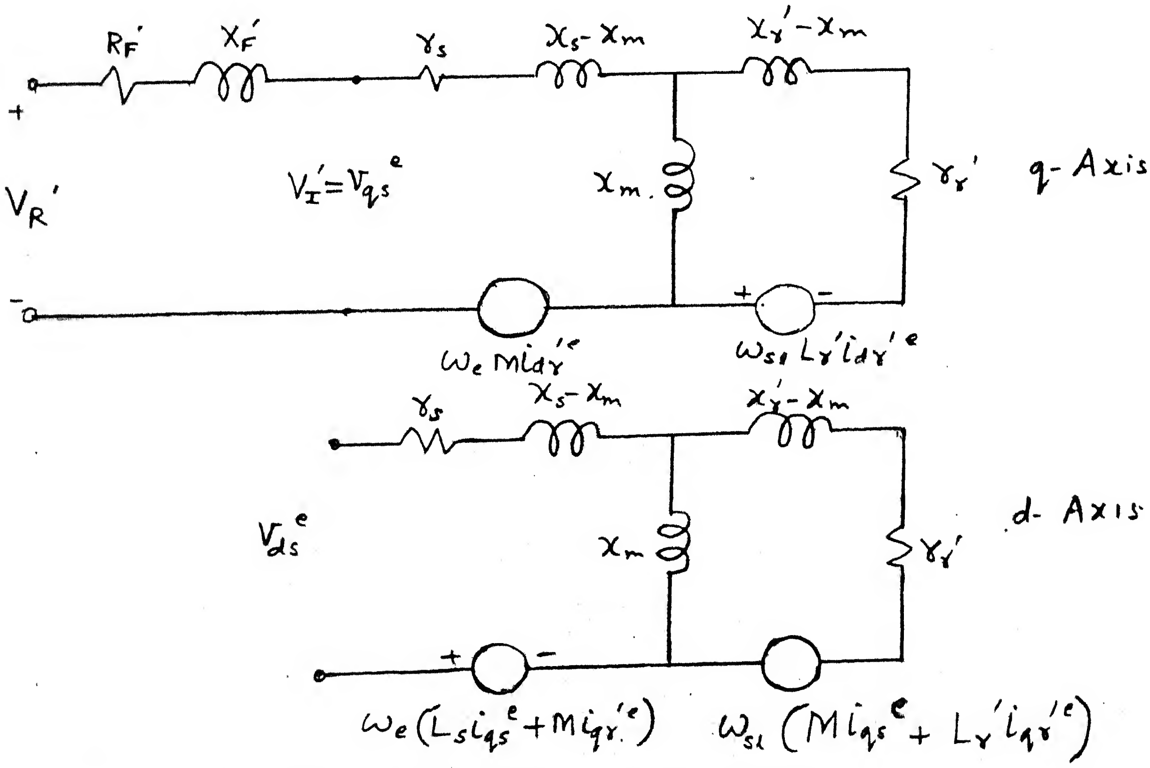


Fig. 3.7 Simplified d-q equivalent circuit

CHAPTER 4

ANALYSIS OF CONTROLLED CURRENT INDUCTION MOTOR DRIVE

4.1 INTRODUCTION:

In the previous chapter, we developed a complete model of the current source inverter fed induction motor. In this chapter steady state characteristics of the drive has been obtained and compared with voltage source inverter drive. Also a linearized model for open loop and closed loop operation around an operating point is developed. The linearized model is utilized for stability and transient response analysis of open and close loop drives with various controllers.

4.2 STEADY-STATE CHARACTERISTICS:

In steady state, in the synchronous reference frame, all currents and voltages will be constant provided harmonics are neglected. Thus all the derivatives or 'p' terms in Eqn. (3.32) are zero. Hence the steady-state machine equation is described as

$$\begin{bmatrix} v^e_{qs} \\ v^e_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s & \omega_e L_s & 0 & \omega_e M \\ -\omega_e L_s & r_s & -\omega_e M & 0 \\ 0 & \omega_{sl} M & r'_r & \omega_{sl} L'_r \\ -\omega_{sl} M & 0 & -\omega_{sl} L'_r & r'_r \end{bmatrix} \begin{bmatrix} i^e_{qs} \\ 0 \\ i'^e_{qr} \\ i'^e_{dr} \end{bmatrix} \quad (4.1)$$

Solving equations (3.43), (3.58) and (4.1) we get

$$T_e = 3\ I_r^{\,2}\ \frac{\omega_e M^2 s}{r_r[1+(\frac{s\omega L_r'}{r_r'})^2]} \tag{4.2}$$

$$T_e = 3\ \frac{1}{\omega_e}\ I_R^{\,2}\ \frac{X_m^{\,2}\ r_r'/s}{[(r_r'/s)^2 + (X_m+X_{1r}')^2]} \tag{4.3}$$

Equation (4.3) is the standard relationship for induction motor torque. The steady state equivalent circuit is shown in Fig. 4.1. From the equivalent circuit, we have

$$I'^2_r = \frac{X_m^{\,2}}{(r_r'/s)^2 + (X_m+X_{1r}')^2}\ I_R^{\,2} \tag{4.4}$$

$$T_e = \frac{3}{\omega_e}\ I_r'^2\ \frac{r_r'}{s} \tag{4.5}$$

The steady-state slip-torque characteristics for a current controlled induction motor drive are shown in Fig. 4.2. The parameters for the induction motor used are given in Appendix III.

4.2.1 Comparison of Performance between current source and Voltage Source Drives:

In Table 4.1 various formulas which determine the motor characteristics are shown for the two types of drives: current source type and voltage source type. These formulas are derived from eqn. (4.1) and from corresponding equations applied

to the motor fed with voltage source inverter with 180° conduction. It is noted that the formulas for efficiency are the same for both types[5].

The resulting currents from eqn. (4.1) are used to compute the flux linkages [7] from eqn. (3.10). The results for the voltage source and the current source supplied motor are shown in Figs. 4.3 and 4.4. A comparison of the torque speed curves shows that the current source drive results in much less torque at low speeds but has a sharp peak closer to synchronous speed than the voltage source type. We also note that there is sharp rise in flux linkage as the slip approaches zero. This results in saturation and high losses in a practical machine. Thus operation at full current at low slip is to be avoided.

4.2.2 Linearized Model for Open Loop Operation:

One method available to study the transient performance of electric drives is perturbation analysis about an operating point. Small displacement theory has been very effective in studying stability [2,5]. This theory enables to establish linear equations which describe operation of a system for small changes about an operating point.

Each variable is considered to be composed of a steady - state and small-time varying component. For example:

$$i_{qs}^{e} = i_{qso}^{e} + \Delta i_{qs}^{e} \tag{4.6}$$

$$i_{dr}^{e} = i'_{dro} + \Delta i_{dr}^{e\prime} \tag{4.7}$$

$$i'^{e}_{qr} = i'^{e}_{qro} + \Delta i'^{e}_{qr} \tag{4.8}$$

$$\omega_r = \omega_{ro} + \Delta\omega_r \tag{4.9}$$

$$V'_R = V'_{Ro} + \Delta V_R' \tag{4.10}$$

$$\omega_e = \omega_{eo} + \Delta\omega_e \tag{4.11}$$

$$T_L = T_{Lo} + \Delta T_L \tag{4.12}$$

These components are substituted into the original nonlinear equations (3.57) and (3.58). All purely steady-state terms drop out and all second-order perturbation terms are ignored. The resulting equations are linear in the perturbation variables which allows us to use linear control analytical techniques to synthesize the needed control.

The linearized equations in matrix form are

$$\begin{bmatrix} L & M & 0 & 0 \\ M & L_r' & 0 & 0 \\ 0 & 0 & L_r' & 0 \\ 0 & 0 & 0 & \frac{-2J}{P} \end{bmatrix} p \begin{bmatrix} \Delta i_{qs}^{e} \\ \Delta i'^{e}_{qr} \\ \Delta i'^{e}_{dr} \\ \Delta \omega_r \end{bmatrix} =$$

$$
= - \begin{bmatrix} R & 0 & \omega_e M & 0 \\ 0 & r'_r & \omega_{slo} L'_r & -L'_r i'^{e}_{dro} \\ -\omega_{slo} M & -\omega_{slo} L'_r & r'_r & M i^{e}_{qso} + L'_r i'^{e}_{qro} \\ \frac{3P}{4} M i'^{e}_{dro} & 0 & \frac{3P}{4} M i^{e}_{qso} & 0 \end{bmatrix} \begin{bmatrix} \Delta i^{e}_{qs} \\ \Delta i'^{e}_{qr} \\ \Delta i'^{e}_{dr} \\ \Delta \omega_r \end{bmatrix}
$$

$$
+ \begin{bmatrix} -M i'^{e}_{dro} & 1 & 0 \\ -L'_r i'^{e}_{dro} & 0 & 0 \\ M i^{e}_{qso} + L'_r i'^{e}_{qro} & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta \omega_e \\ \Delta V'_R \\ \Delta T_L \end{bmatrix} \tag{4.13}
$$

where,

$$
L = L_F' + L_S \tag{4.14}
$$

$$
R = r_s + R_F' \tag{4.15}
$$

If both sides of this matrix equation are premultiplied by the inverse of the coefficient matrix of the derivative vector, the resulting equations are arranged in state variable form.

$$
p \begin{bmatrix} \Delta \underline{i} \\ \Delta \omega_r \end{bmatrix} = [A] \begin{bmatrix} \Delta \underline{i} \\ \Delta \omega_r \end{bmatrix} + [B] [\Delta \underline{u}] \tag{4.16}
$$

where,

$$
[B] = \begin{bmatrix} 0 & L_r'/L_1 & 0 \\ -i'^{e}_{dro} & M/L_1 & 0 \\ \frac{M i_{qso} + L_r' i'^{e}_{dro}}{L_r'} & 0 & 0 \\ 0 & 0 & -\frac{P}{2J} \end{bmatrix}
$$

where,

$$\Delta \underline{i} = \begin{bmatrix} \Delta i_{qs}^{e} \\ \Delta i_{qr}^{\prime e} \\ \Delta i_{dr}^{\prime e} \end{bmatrix} \quad ; \quad [\Delta \underline{u}] = \begin{bmatrix} \Delta \omega_e \\ \Delta V_R' \\ \Delta T_L \end{bmatrix} \tag{4.17}$$

$$[A] = \begin{bmatrix} \frac{-L_r' R}{L_1} & \frac{M r_r'}{L_1} & \frac{-M L_r' \omega_{ro}}{L_1} & \frac{-M L_r' i_{dro}^{\prime e}}{L_1} \\ \frac{MR}{L_1} & -\frac{L r_r'}{L_1} & \frac{L_r' L \omega_{ro} - \omega_e}{L_1} & \frac{L_r' L\, i_{dro}^{\prime e}}{L_1} \\ \frac{M \omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r'}{L_r'} & \frac{-M i_{qso} - L_r' i_{qro}^{\prime e}}{L_r'} \\ \frac{3}{8} \frac{P^2 M i_{dro}^{\prime e}}{J} & 0 & \frac{3}{8} \frac{P^2 M i_{qso}^{e}}{J} & 0 \end{bmatrix} \tag{4.18}$$

$$L_1 = L L_r' - M^2 \tag{4.19}$$

4.2.3 Calculation of Transfer Function for Open Loop Drive:

In this study, the Levrrier-Faddeev [27] method given in Appendix II is used to find the characteristic equation of the system of eqns. (4.16). The roots of the characteristic equation gives the poles or eigen values of the system.

To define a complete transfer function it is also necessary to determine the zeros. These are unique to the

choice of input and output while the poles are characteristics of the system. One method of obtaining the zeroes involves transformation of the system equations to the phase variable form. Such a transformation is done using a recursive algorithm described by Tuel [15] and Rane [16] and is given in Appendix II. The algorithm provides a polynomial equation whose roots are the zeroes of the transfer function. Thus, for a particular operating point and a particular choice of input and output, the complete transfer function is found.

4.2.4 Stability Analysis of Open Loop Drive:

Only a small portion of the slip-torque characteristics is shown in Fig. 4.2. Examination of the characteristics indicates two regions of operation - one with positive slope and the other with negative slope. The negative sloped portions are well known to be inherently unstable. This type of instability will be referred to as a static instability. It is also possible to have dynamic instability on either portion of the characteristics. This is caused by negative electrical damping which is highly dependent on the selection of operating point and machine parameters.

For controlled current inverter operation, the steady - state operating point can occur on either the upper lower portion of the characteristic. For example, if operation is constrained such that the machine is never driven into a highly saturated condition, operation would be at point A.

Operation at point B, which yields the same output torque, corresponds to a highly saturated condition. For low torque and rated flux conditions, the steady-state operating point would be on the upper portion of a low current magnitude characteristic, for example, at point C which is on the statically stable side of the I_R = 40A characteristic.

The open loop system shown in Fig. 4.5 is described by equation (4.16) for small disturbances about a steady-state point. For a specific input two of the three elements of $[\Delta u]$ are set equal to zero. The transfer function is obtained in factored form. Stability and transient response are immediately apparent from the pole-zero locations.

If open-loop operation is attempted by applying an uncontrolled rectifier voltage and by commanding a constant inverter switching frequency (no current or slip control), the drive will be unstable. We examine the transfer function $\Delta I_R'/\Delta V_R'$. The transfer function for open-loop operation corresponding to four different points are given in Table 4.2.

It is seen from the Table 4.2 that the system is dynamically unstable at all four operating points. This type of instability results in one right-half plane pole in the linearized transfer function. In addition, for unsaturated conditions with sizable torque output, the system is also statically unstable which results in a second pole in the

right-half plane at point A. Therefore closed-loop control is imperative for stable operation.

4.3 CLOSED-LOOP CONTROL ANALYSIS:

On examining equation (4.17) we see that two control variables are available for system stabilization. These system inputs are the rectifier voltage and the frequency command to the inverter. We will now study the improvement in stability provided by the particular feedback.

4.3.1 Slip Frequency Control:

With slip frequency control, incremental changes in rotor speed are related to incremental changes in electrical frequency by the constraint

$$\Delta\omega_e = \Delta\omega_r + \Delta\omega_{sl} \tag{4.20}$$

Slip frequency control forces electrical frequency to change in response to rotor speed, which tends to maintain a constant angular displacement between rotor and stator MMF's during both steady-state and transient conditions.

The system for slip frequency control is described by

$$p[\Delta x] = [A]\,[\Delta x] + [B]\,[\Delta u] \tag{4.21}$$

where,

$$[\Delta x]^t = [\,\Delta i_{qs}^e \quad \Delta i_{qr}'^e \quad \Delta i_{dr}'^e \quad \Delta\omega_r\,] \tag{4.22}$$

$$[\Delta u]^t = [\Delta \omega_{sl} \;\; \Delta V_R' \;\; \Delta T_L] \tag{4.23}$$

$$[A] = \begin{bmatrix} \frac{-L_r' R}{L_1} & \frac{M r_r'}{L_1} & \frac{-M L_r' \omega_{ro}}{L_1} & \frac{-L_r' M i_{dro}'^{e}}{L_1} \\ \frac{MR}{L_1} & \frac{-L r_r'}{L_1} & \frac{L_r' L \omega_{ro} - \omega_e}{L_1} & \frac{M^2 i_{dro}'^{e}}{L_1} \\ \frac{M \omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r'}{L_r'} & 0 \\ \frac{3}{8}\frac{P^2 M i_{dro}'^{e}}{J} & 0 & \frac{3}{8}\frac{P^2 M i_{qso}^{e}}{J} & 0 \end{bmatrix} \tag{4.24}$$

The matrix [B] remains unaffected.

If the closed-loop operation is attempted by applying an uncontrolled rectifier voltage and by controlling the inverter switching frequency (no current control but slip control), the drive is stable in positive slope portion only and unstable in negative slope portion. This is seen by calculating the transfer functions $\Delta I_R'/\Delta V_R'$ or $\frac{\Delta \omega_r}{\Delta \omega_{sl}}$. The transfer functions for slip control corresponding to four different points are given in Table 4.4 and Table 4.5.

We see from the table 4.4 that the system is dynamically as well as statically stable in positive sloped region because all the eigen-values of the system are lying in the left-half plane at point A and C. The system is dynamically as well as statically unstable in negative sloped region because of two eigen values of the system at B and D are lying in the right-half

plane. Thus we see that there is improvement in stability with slip control compare to uncontrolled open loop operation. Although this type of control has a stabilizing effect, it is not capable of ensuring stable operation under all operating conditions.

4.3.2 Independent Current and Slip Frequency Control using Proportional Controller:

To obtain steady-state current control along with improved system transient response, the rectifier voltage must be constrained to respond to the error between a commanded value and the actual value of the dc link current. A proportional controller is used for this purpose. The rectifier voltage can then be expressed as

$$\Delta V_R' = K_1 \; (\Delta I_R'^{*} - \Delta I_R') \tag{4.25}$$

The system matrix equation including the slip frequency and current magnitude control using proportional controller shown in Fig. 4.6 is

$$p[\Delta x] = [A] \; [\Delta x] + [B] \; [\Delta u] \tag{4.26}$$

where,

$$[\Delta u]^t = [\Delta \omega_{sl} \;\; \Delta I_R'^{*} \;\; \Delta T_L \;] \tag{4.27}$$

$$[A] = \begin{bmatrix} \frac{-L_r{}'R'}{L_1} & \frac{Mr_r'}{L_1} & \frac{-ML_r{}'\omega_{ro}}{L_1} & \frac{-L_r{}'M\ i'^{e}_{dro}}{L_1} \\ \frac{MR'}{L_1} & \frac{-L\ r_r'}{L_1} & \frac{L_r{}'L\ \omega_{ro}-\omega_e}{L_1} & \frac{M^2\ i'^{e}_{dro}}{L_1} \\ \frac{M\omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r'}{L_r'} & 0 \\ \frac{3}{8}\ \frac{P^2Mi'^{e}_{dro}}{J} & 0 & \frac{3}{8}\ \frac{P^2M\ i^{e}_{qso}}{J} & 0 \end{bmatrix} \tag{4.28}$$

$$[B] = \begin{bmatrix} 0 & \frac{K_1L_r{}'}{L_1} & 0 \\ -i'^{e}_{dro} & \frac{-K_1M}{L_1} & 0 \\ \frac{(Mi^{e}_{qso}+L_r'i'^{e}_{dro})}{L_r{}'} & 0 & 0 \\ 0 & 0 & \frac{-P}{2J} \end{bmatrix} \tag{4.29}$$

where $R' = R + Kl$

And for frequency control the matrix A becomes

regulator. Hence,

$$\Delta I_R'^{*} = K_2 \left(\Delta\omega_r^{*} - \Delta\omega_r \right) \tag{4.31}$$

Using equations (4.25) and (4.31), we get the matrix equation for the system shown in Fig. 4.7 as

$$p[\Delta x] = [A]\,[\Delta x] + [B]\,[\Delta u] \tag{4.32}$$

where

$$[A] = \begin{bmatrix} \dfrac{-L_r'R'}{L_1} & \dfrac{Mr_r'}{L_1} & \dfrac{-ML_r'\omega_{ro}}{L_1} & \dfrac{-(K_1L_r' + ML_r'i_{dro}'^{e})}{L_1} \\ \dfrac{MR'}{L_1} & \dfrac{-Lr_r'}{L_1} & \dfrac{L_r'L\omega_{ro} - \omega_e}{L_1} & \dfrac{(K_1M + LL_r'i_{dro}'^{e})}{L_1} \\ \dfrac{M\omega_{slo}}{L_r'} & \omega_{slo} & \dfrac{-r_r'}{L_r'} & \dfrac{-(Mi_{qso}^{e} + L_r'i_{qro}'^{e})}{L_r'} \\ \dfrac{3}{8}\,\dfrac{P^2M\,i_{dro}'^{e}}{J} & 0 & \dfrac{3}{8}\,\dfrac{P^2M\,i_{qso}^{e}}{J} & 0 \end{bmatrix} \tag{4.33}$$

$$[B] = \begin{bmatrix} 0 & \dfrac{K_1K_2L_r'}{L_1} & 0 \\ -i_{dro}'^{e} & \dfrac{-K_1K_2M}{L_1} & 0 \\ \dfrac{(Mi_{qso}^{e} + L_r'i_{qro}'^{e})}{L_r'} & 0 & \dfrac{-P}{2J} \end{bmatrix} \tag{4.34}$$

$$[\Delta u]^t = [\Delta\omega_e \;\; \Delta\omega_r^{*} \;\; \Delta T_1] \tag{4.35}$$

The transfer function for independent speed and slip frequency control is obtained by replacing ω_e by ω_{sl} in the independent variable vector [Δu]. Also the column of matrix A associated with ω_r is changed to correspond to $\omega_{sl} = \omega_s - \omega_r$. Thus the matrix A is

$$[A] = \begin{bmatrix} \frac{-L_r'R'}{L_1} & \frac{Mr_r'}{L_1} & \frac{-ML_r'\omega_{ro}}{L_1} & \frac{-(K_1L_r'+ML_r'i_{dro}'^e)}{L_1} \\ \frac{MR'}{L_1} & \frac{-Lr_r'}{L_1} & \frac{L_r'L\omega_{ro}-\omega_e}{L_1} & \frac{(K_1M + M^2\, i_{dro}'^e)}{L_1} \\ \frac{M\omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r'}{L_r'} & 0 \\ \frac{3}{8}\,\frac{P^2Mi_{dro}'^e}{J} & 0 & \frac{3}{8}\,\frac{P^2M\, i_{qso}^e}{J} & 0 \end{bmatrix} \tag{4.36}$$

The transfer functions $\Delta\omega_r / \Delta\omega_r^*$, $\frac{\Delta\omega_r}{\Delta\omega_e}$ and $\frac{\Delta\omega_r}{\Delta\omega_{sl}}$ have been calculated and are shown in Tables 4.10, 4.11 4.12 and 4.13.

We observe that the system is dynamically as well as statically stable under all operating conditions as all the eigen-values of the system lie in the left-half plane for all the four points.

By looking at the location of the poles of the system we see that it is relatively more stable than independent current and slip frequency control.

4.3.4 Independent Speed and Slip Frequency Control using Proportional Plus Integral Controller:

We now use an integral plus proportional controller to give satisfactory speed of response with zero steady-state error. The current magnitude is set by the error between the reference speed and actual speed through a proportional plus integral controller. Hence,

$$\Delta I_R'^{*} = \frac{K_2(1+p\tau)}{p} \left(\Delta\omega_r^{*} - \Delta\omega_r\right) \tag{4.37}$$

To include the compensator in the analysis, a fifth state variable ΔQ is defined. ΔQ is defined to be the output of the integral controller, that is

$$\Delta Q = \frac{K_2}{p} \left(\Delta\omega_r^{*} - \Delta\omega_r\right) \tag{4.38}$$

The reference current can then be expressed as

$$\Delta I_R'^{*} = \Delta Q\,(1 + \tau p) \tag{4.39}$$

Using equations (4.25), (4.37) and (4.38) we get the system matrix equation for integral plus proportional controller shown in Fig. 4.8 in the state space form as

$$p[\Delta x] = [A]\,[\Delta x] + [B]\,[\Delta u] \tag{4.40}$$

where,

$$[A] = \begin{bmatrix} \frac{-L_r'R'}{L_1} & \frac{Mr_r'}{L_1} & \frac{-ML_r'\omega_{ro}}{L_1} & \frac{K_1L_r'}{L_1} & \frac{-(K_1K_2\tau L_r'+ML_r'i'^{e}_{dro})}{L_1} \\ \frac{MR'}{L_1} & \frac{-Lr_r'}{L_1} & \frac{L_r'L\omega_{ro}-\omega_e}{L_1} & \frac{-K_1M}{L_1} & \frac{(K_1K_2\tau M+LL_r'i'^{e}_{dro})}{L_1} \\ \frac{M\ \omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r'}{L_r'} & 0 & \frac{-(M\ i^{e}_{qso}+L_r'i'^{e}_{qro})}{L_r'} \\ 0 & 0 & 0 & 0 & -K_2 \\ \frac{3}{8}\ \frac{P^2\ Mi'^{e}_{dro}}{J} & 0 & \frac{3}{8}\ \frac{P^2M\ i^{e}_{qso}}{J} & 0 & 0 \end{bmatrix} \tag{4.41}$$

$$[B] = \begin{bmatrix} 0 & \frac{K_1K_2\tau L_r'}{L_1} & 0 \\ -i'^{e}_{dro} & \frac{-K_1K_2\tau M}{L_1} & 0 \\ \frac{(Mi^{e}_{qso}+L_r'i'^{e}_{qro})}{L_r'} & 0 & 0 \\ 0 & K_2 & 0 \\ 0 & 0 & \frac{-P}{2J} \end{bmatrix} \tag{4.42}$$

$$[\Delta x]^t = [\ \Delta i^{e}_{qs} \quad \Delta i'^{e}_{qr} \quad \Delta i'^{e}_{dr} \quad \Delta Q \quad \Delta\omega_r] \tag{4.43}$$

The transfer function for independent speed and slip frequency control with PI controller is obtained by replacing ω_e by equation (4.20). Thus the matrix A for the system is

$$[A]=\begin{bmatrix} \frac{-L_r'R'}{L_1} & \frac{Mr_r'}{L_1} & \frac{-ML_r'\omega_{ro}}{L_1} & \frac{K_1L_r'}{L_1} & \frac{-(K_1K_2\tau L_r'+ML_r'i_{dro}'^e)}{L_1} \\ \frac{MR'}{L_1} & \frac{-Lr_r'}{L_1} & \frac{L_r'L\omega_{ro}-\omega_e}{L_1} & \frac{-K_1M}{L_1} & \frac{(K_1K_2\tau M+M^2 i_{dro}'^e)}{L_1} \\ \frac{M\omega_{slo}}{L_r'} & \omega_{slo} & \frac{-r_r}{L_r'} & 0 & 0 \\ 0 & 0 & 0 & 0 & -K_2 \\ \frac{3}{8}\,\frac{P^2Mi_{dro}'^e}{J} & 0 & \frac{3}{8}\,\frac{P^2Mi_{qso}^e}{J} & 0 & 0 \end{bmatrix} \qquad (4.44)$$

The transfer function $\Delta\omega_r/\Delta\omega_r^*$, $\Delta\omega_r/\Delta\omega_e$ and $\Delta\omega_r/\Delta\omega_{sl}$ for four different operating points are shown in Tables 4.14, 4.15, 4.16 and 4.17.

We see that all the poles are lying in the left half plane so that system is stable under all operating conditions.

4.4 EFFECT OF CONTROLLER GAIN ON STABILITY:

The location of poles and zeroes depend on the operating point as shown in Table 4.2. When the controller gain is increased, the system may or may not be stable for all values of gain. The root locus for the transfer function $\Delta I_R'/\Delta I_R'^*$ corresponding to point A is shown in Fig. 4.9. As the gain is increased, the pole in the right half plane moves towards left-half plane and crosses the imaginary axis at $K_1 = 1.25$. So we see that though the open-loop system is unstable but the close loop system is stable for the values of gain greater than 1.25 corresponding to point A.

The Fig. 4.10 shows the root locus for the transfer function $\Delta I_R'/\Delta I_R'^*$ corresponding to point B. As the gain is increased the system becomes stable at K_1 equal to 1.2 because all the poles lie in the left-half plane. It becomes unstable beyond K_1 equal to 1.4 because one pole always lies in the right half plane.

The root locus for the transfer function $\Delta\omega_r/\Delta\omega_r^*$ with proportional plus integral is shown in Figs. 4.11 and 4.12. Corresponding to, point A and B we see that the system is stable for all values of gain. For large values of gain the system corresponding to point A is more damped than corresponding to point B.

For a particular of gain the system may or may not be stable various operating points along the steady state curve. So adaptive controller may be used for operating in the whole range of torque-slip characteristic.

4.5 COMPARISON OF TRANSIENT RESPONSE FOR VARIOUS CONTROL METHODS:

The Table 4.18 shows the rise time, delay time, percentage peak overshoot and setting time of different controls methods. It can be seen that open loop transient response is fast but the percentage peak overshoot is high and system is very under-damped. With the help of proportional controller the system can be made over-damped or critically damped by varying controller gain. The transient response corresponding to transfer function $\Delta\omega_r / \Delta\omega_r^*$ with proportional plus integral controller has smaller percentage peak overshoot compared to open loop operation and its rise time is lower than the transfer function corresponding to $\Delta I_R / \Delta I_R^*$.

TABLE 4.1

COMPARISON OF PERFORMANCE FORMULA BETWEEN CURRENT SOURCE AND VOLTAGE SOURCE DRIVES

	Current source type	Voltage source type
Torque	$3\,\dfrac{S^2\omega_e^2M^2r_r'I_R^{\;2}}{r_r'^2+S^2\omega_e^2L_r'^2}$	$\dfrac{\pi^2}{18}\cdot\dfrac{S\omega_eM^2r_r'}{(r_sr_r'-S\omega_e^2L_sL_r\sigma)^2+\omega_e^2(r_r'L_s+Sr_sL_r')^2}$
Efficiency $(\eta)^{**}$		$\dfrac{S(1-S)\,\omega_e^2\,M^2\,r_r'}{r_s(r_r'^2+S^2\omega_e^2\,L_r'^2)+S\omega_e^2\,M^2r_r'}$

$$** \qquad \eta = \frac{\text{Mechanical output}}{\text{Input}}$$

(Iron loss neglected)

$$\text{where} \quad \sigma = 1 - \frac{M^2}{L_sL_r'}$$

TABLE 4.2

OPEN LOOP TRANSFER FUNCTION $\Delta I_R'/\Delta V_R'$ FOR UNCONTROLLED OPERATION AT $f_c = 50$ Hz.

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	$-1.46 \pm j31.79$ -2.21	$-28.55 \pm j50.41$ 37.42 -2.31
B	0.02	60	62.27	$-6.11 \pm j16.1$ 7.1	$-22 \pm j26.9$ $11 \pm j11.1$
C	0.002	40	18.31	$-1.36 \pm j21.9$ -2.4	$-21.99 \pm j33.9$ 24.55 -2.56
D	0.033	40	18.44	$-5.39 \pm j13.2$ 5.7	$5.8 \pm j18.7$ -20.5 -13.2

TABLE 4.3

OPEN LOOP TRANSFER FUNCTION $\Delta\omega_r / \Delta w_e$ FOR UNCONTROLLED OPERATION AT $f_e = 50$ Hz.

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	-2.23	$-28.6 \pm j50.4$
				-1.18	37.42
					-2.3
B	0.02	60	62.27	12.52	$-22 \pm j26.9$
				-1.3	$11 \pm j11.1$
C	0.002	40	18.31	-2.4	$-21.99 \pm j33.9$
				-0.38	24.5
					-2.56
D	0.033	40	18.44	37.9	$5.8 \pm j18.7$
				-0.4	-20.5
					-13.2

TABLE 4.4

TRANSFER FUNCTION $\Delta I_R'/\Delta V_R'$ FOR SLIP FREQUENCY CONTROL at $f_e = 50$ Hz.

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	$-2.56 \pm j0.94$	$-3.59 \pm j10.7$ -13.3 -1.48
B	0.02	60	62.27	$-2.56 \pm j6.3$	$1.6 \pm j18.7$ -23.02 -2.24
C	0.002	40	18.31	$-2.56 \pm j0.63$	-18.2 $-1.62 \pm j6.8$ -0.57
D	0.033	40	18.44	$-2.56 \pm j10.37$	$4 \pm j4.9$ -29.3 -0.7

TABLE 4.5

TRANSFER FUNCTION $\Delta\omega_r/\Delta\omega_{sl}$ FOR SLIP FREQUENCY CONTROL AT $f_e = 50$ Hz.

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	125.62	$-3.59 \pm j10.69$
				-2.29	-13.3
					-1.48
B	0.02	60	62.27	137.34	$1.63 \pm j18.66$
				12.3	-23.02
					-2.24
C	0.002	40	18.31	84.91	-18.18
				-2.52	$-1.62 \pm j6.98$
					-0.57
D	0.003	40	18.44	88.75	$4.01 \pm j20.86$
				36.15	-29.34
					-0.67

TABLE 4.6

TRANSFER FUNCTION $\Delta I_R'/\Delta I_R^*$ WITH INDEPENDENT CURRENT AND INPUT FREQUENCY CONTROL AT f_e = 50 Hz.

Point	Slip	I_R (A)	K_1	T_e (N-m)	Zeroes	Poles
A	0.003	60	1.3	57.7	$-1.46\pm j31.8$ -2.21	-143.1 $-6.03\pm j7.04$ -0.91
B	0.02	60	1.3	62.27	$-6.1\pm j16.1$ 7.1	-148.8 $-3.06\pm j8.1$ -1.2
C	0.002	40	1.3	18.31	$-1.3\pm j21.9$ -2.41	-148.6 $-2.7\pm j12.6$ -2.14
D	0.033	4.0	0.8	18.44	$-5.4\pm j13.2$ 5.66	-99.8 $-2.16\pm j14.45$ -0.36

TABLE 4.7

TRANSFER FUNCTION $\Delta \omega_r / \Delta \omega_e$ FOR INDEPENDENT CURRENT AND INPUT FREQUENCY CONTROL AT f_e = 50 Hz.

Point	Slip	I_R (A)	K_1	T_e (N-m)	Zeroes	Poles
A	0.003	60	1.3	57.7	-9.92 -0.86	-143.1 -6.03±j7.04 -0.91
B	0.02	60	1.3	62.27	17.3 -1.71	-148.8 -3.06±j8.1 -1.2
C	0.002	40	1.3	18.31	-49.51 -2.2	-148.6 -2.7±j12.6 -2.14
D	0.033	40	0.8	18.44	43.34 -0.96	-99.8 -2.16±j14.45 -0.36

TABLE 4.8

TRANSFER FUNCTION $\Delta I_R'/\Delta I_R'^*$ WITH INDEPENDENT CURRENT AND SLIP FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER AT f_e = 50 Hz.

Point	Slip	I_R (A)	K_1	T_e (N-m)	Zeroes	Poles
A	0.003	60	1.3	57.7	$-2.56 \pm j0.94$ -0.0001	-149.9 $-2.48 \pm j2.8$ -1.2
B	0.02	60	1.3	62.27	$-2.56 \pm j6.28$	-150.0 $-2.37 \pm j9.3$ -1.3
C	0.002	40	1.3	18.31	$-2.56 \pm j0.63$ -0.0001	-150.8 $-2.48 \pm j2.24$ -0.31
D	0.033	40	0.8	18.44	$-2.56 \pm j10.37$	-100.26 $-1.9 \pm j14.88$ -0.39

TABLE 4.9

TRANSFER FUNCTION $\Delta\omega_r/\Delta\omega_{sl}$ FOR INDEPENDENT CURRENT AND SLIP FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER AT f_c = 50 Hz.

Point	Slip	I_R (A)	K_1	T_e (N-m)	Zeroes	Poles
A	0.003	60	1.3	57.5	-9.92	-149.95
					-0.86	$-2.5\pm j2.84$
						-1.18
B	0.02	60	1.3	62.27	17.27	-150.03
					-1.7	$-2.37\pm j9.3$
						-1.31
C	0.002	40	1.3	18.31	-49.5	-150.8
					-2.2	$-2.5\pm j2.24$
						-0.32
D	0.033	40	0.8		43.34	-100.26
					-0.96	$-1.9\pm j14.9$
						-0.39

TABLE 4.10

TRANSFER FUNCTION $\Delta\omega_r/\Delta\omega_r^*$ FOR INDEPENDENT CURRENT AND FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER

$f = 50$ Hz, $K_1 = 1.3$, $K_2 = 1$

Points	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	$-2.56 \pm j2.9$	-137.3 -1.6 $-8.6 \pm j5.2$
B	0.02	60	62.27	$-2.56 \pm j9.25$	-142.9 $-2.27 \pm j8.2$ -8.56
C	0.002	40	18.31	$-2.56 \pm j2.7$	-146.1 $-3.86 \pm j12.7$ -2.25
D	0.033	40	18.44	$-2.56 \pm j14.88$	-148.67 $-3.2 \pm j13.75$ -1.03

TABLE 4.11

TRANSFER FUNCTION $\Delta\omega_r/\Delta\omega_e$ FOR INDEPENDENT CURRENT AND FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER

$f = 50$ Hz, $K_1 = 1.3$, $K_2 = 1$

Points	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	-6.5	-137.3
				-2.2	$-8.6 \pm j5.2$
					-1.6
B	0.02	60	62.27	12.61	-143.0
				-6.7	$-2.27 \pm j8.18$
					-8.56
C	0.002	40	18.31	-3.92	-146.1
				-2.4	$-3.9 \pm j12.7$
					-2.55
D	0.33	40	18.44	38.05	-148.67
				-4.05	$-3.1 \pm j13.75$
					-1.03

TABLE 4.12

TRANSFER FUNCTION $\Delta\omega_r / \Delta\omega_r^*$ FOR INDEPENDENT CURRENT AND SLIP FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER

$f = 50$ Hz, $K_1 = 1.3$, $K_2 = 1$

Points	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	$-2.56 \pm j2.9$	-144.7 $-2.52 \pm j2.94$ -6.36
B	0.02	60	62.27	$-2.56 \pm j9.24$	-144.35 $-2.44 \pm j9.39$ -6.86
C	0.002	40	18.31	$-2.56 \pm j2.7$	-148.4 $-2.08 \pm j2.48$ -3.59
D	0.033	40	18.44	$-2.56 \pm j14.9$	-148.8 $-1.9 \pm j13.6$ -3.26

TABLE 4.13

TRANSFER FUNCTION $\Delta\omega_r / \Delta\omega_{sl}$ FOR INDEPENDENT CURRENT AND SLIP FREQUENCY CONTROL USING PROPORTIONAL CONTROLLER

$f = 50$ Hz, $K_1 = 1.3$, $K_2 = 1$

Points	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	-9.92	-144.7
				-0.86	$-2.52 \pm j2.94$
					-6.36
B	0.02	60	62.27	17.27	-144.4
				-1.71	$-2.44 \pm j9.4$
					-6.86
C	0.002	40	18.31	-49.51	-148.4
				-2.2	$-2.06 \pm j2.48$
					-3.59
D	0.033	40	18.44	-50.36	-148.85
				41.16	$-1.99 \pm j13.6$
					-3.26

TABLE 4.14

TRANSFER FUNCTION $\Delta\omega_r/\Delta\omega_r^*$ WITH INDEPENDENT CURRENT AND FREQUENCY CONTROL USING PI CONTROLLER

Frequency = 50 Hz, K_1 = 1.3, K_2 = 1.0, τ = 0.1

Points	Slip	I_R (A)	Zeroes	Poles
A	0.003	60	-10.0 $-2.56 \pm j2.9$	-142.6 $-6.2 \pm j7.2$ $-0.57 \pm j.74$
B	0.02	60	$-2.56 \pm j9.25$ -10.0	-148.25 $-3.1 \pm j7.97$ $-0.84 \pm j2.5$
C	0.002	40	-10.0 $2.56 \pm j2.71$	-148.37 $-2.8 \pm j12.7$ -2.1 -0.09
D	0.033	40	$-2.56 \pm j14.9$ -10.0	-150.9 $-3.3 \pm j13.9$ $0.73 \pm j1.46$

TABLE 4.15

TRANSFER FUNCTION $\Delta\omega_r / \Delta\omega_e$ WITH INDEPENDENT CURRENT AND INPUT FREQUENCY CONTROL USING PI CONTROLLER

Frequency = 50 Hz, K_1 = 1.3, K_2 = 1.0, τ = 0.1

Points	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	-9.92	-142.6
				-0.86	$-6.2 \pm j7.2$
				-0.0012	$-0.57 \pm j.75$
B	0.02	60	62.27	17.3	-148.25
				-1.71	$-3.1 \pm j7.97$
					$-0.84 \pm j2.5$
C	0.002	40	18.31	-49.5	-148.4
				-2.2	$-2.8 \pm j12.7$
				-0.001	-2.1
					-0.09
D	0.033	40	18.44	-50.36	-150.9
				41.16	$-3.3 \pm j13.9$
					$0.7 \pm j1.5$

TABLE 4.16

TRANSFER FUNCTION $\Delta\omega_r/\Delta\omega_r^*$ WITH INDEPENDENT CURRENT AND SLIP FREQUENCY CONTROL USING PI CONTROLLER

Frequency = 50 Hz, $K_1 = 1.3$, $K_2 = 1.0$, $\tau = 0.1$

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	-10	-149.5
				$-2.56 \pm j2.9$	$-2.5 \pm j2.8$
					$-0.8 \pm j2.2$
B	0.02	60	62.27	$-2.56 \pm j9.25$	-149.5
				-10	$-2.36 \pm j9.3$
					$-0.9 \pm j2.1$
C	0.002	40	18.31	-10.0	-150.6
				$-2.56 \pm j2.7$	$-2.57 \pm j2.23$
					$-0.18 \pm j1.7$
D	0.033	40	18.44	$-2.56 \pm j14.9$	-151
				-10	$-2.23 \pm j13.3$
					$-0.29 \pm j1.68$

TABLE 4.17

TRANSFER FUNCTION $\Delta\omega_r/\Delta\omega_{sl}$ WITH INDEPENDENT CURRENT AND SLIP FREQUENCY CONTROL USING PI CONTROLLER

Frequency = 50 Hz, K_1 = 1.3, K_2 = 1.0, τ = 0.1

Point	Slip	I_R (A)	T_e (N-m)	Zeroes	Poles
A	0.003	60	57.7	-9.92	-149.5
				-0.86	$-2.48\pm j2.8$
				-0.0013	$-0.82\pm j2.17$
B	0.02	60	62.27	17.3	-149.5
				-1.71	$-2.4\pm j9.3$
					$-0.9\pm j2.14$
C	0.002	40	18.31	-49.51	-150.6
				-2.2	$-2.58\pm j2.23$
				-0.0001	-0.18 ± 1.7
D	0.033	40	18.44	-50.36	-151.0
				41.2	-2.23 ± 13.5
					-0.3 ± 1.7

TABLE 4.18

COMPARISON OF TRANSIENT RESPONSE FOR VARIOUS CONTROL METHODS

$K_1 = 1.3$, $K_2 = 1$, $\tau = 0.1$

Transfer Function	Point	Rise time (sec)	Delay time (sec)	% peak overshoot	Setting time (sec)
$\Delta I'_R / \Delta V'_R$	A	0.091	0.06	85%	1.1
$\Delta I'_R / \Delta V'_R$	A	2.3	0.45	Overdamped	4.8
	B	2.6	0.8	Overdamped	4.7
$\Delta I'_R / \Delta I'^{*}_R$	B	1.7	0.68	Overdamped	3.3
$\Delta \omega_r / \Delta \omega^*_r$	A	1.15	0.62	2.5%	2.4
with speed regulator	B	2.5	1.5	Overdamped	3.0
$\Delta \omega_r / \Delta \omega_r^*$	A	0.95	0.4	31%	6.0
with PI controller	B	0.9	0.5	28%	5.7

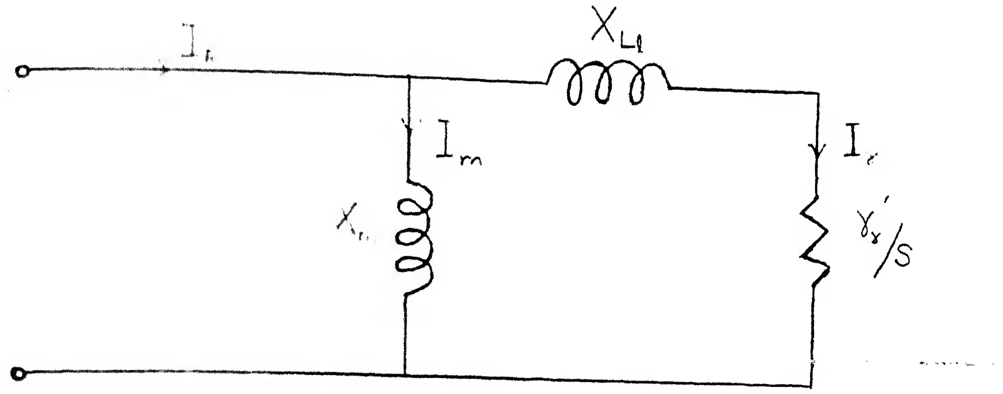


Fig. 4.1 Steady state equivalent circuit of CSI fed Induction motor.

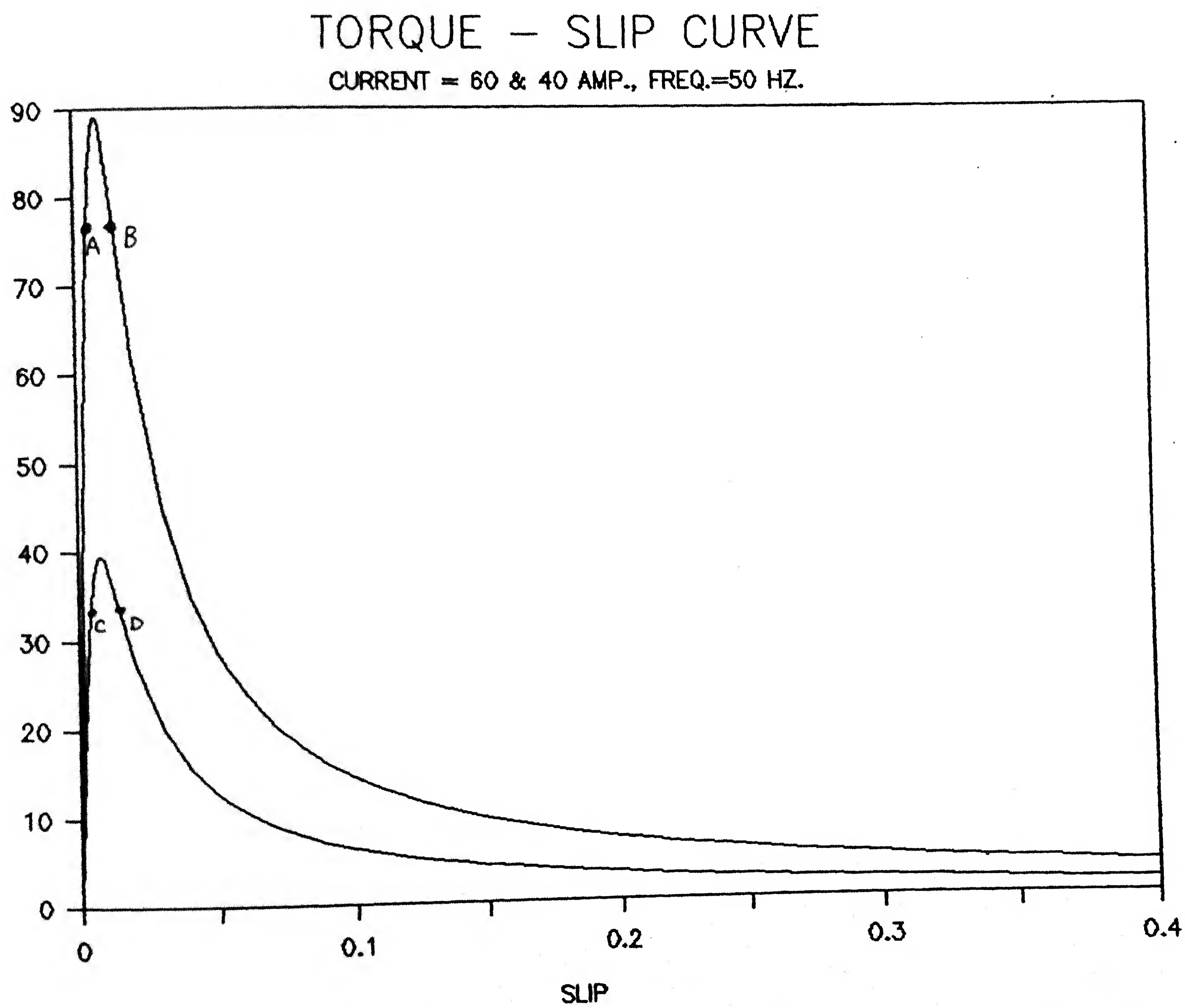


Fig. 4.2 Steady-state controlled curve induction motor characteristics.

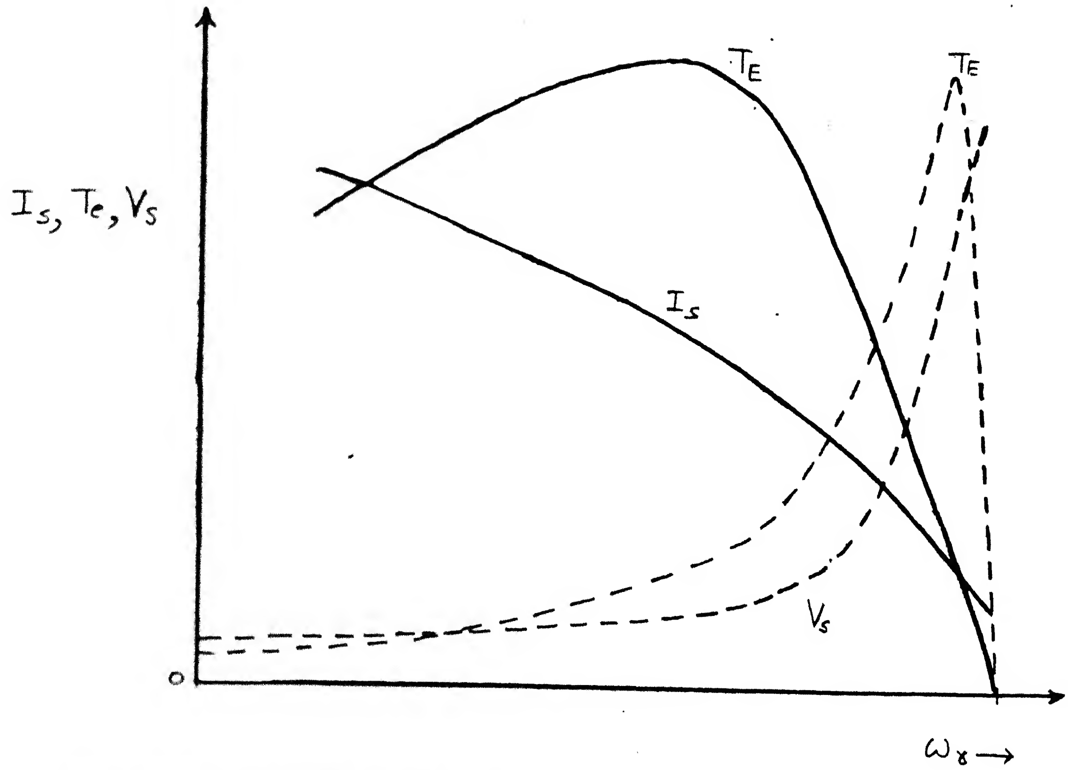


Fig. 4.3 Developed torque and stator voltage and current characteristics.

--- For CSI ——— For VSI

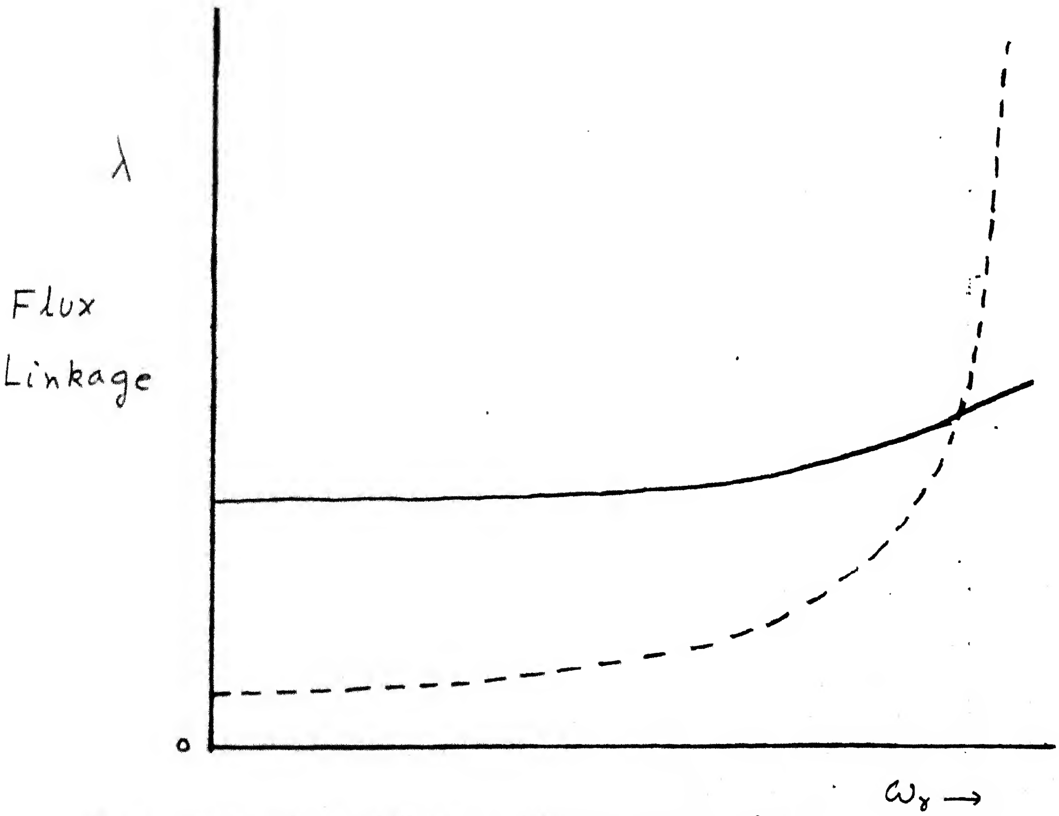


Fig. 4.4 Flux linkage characteristics

--- For CSI ——— For VSI

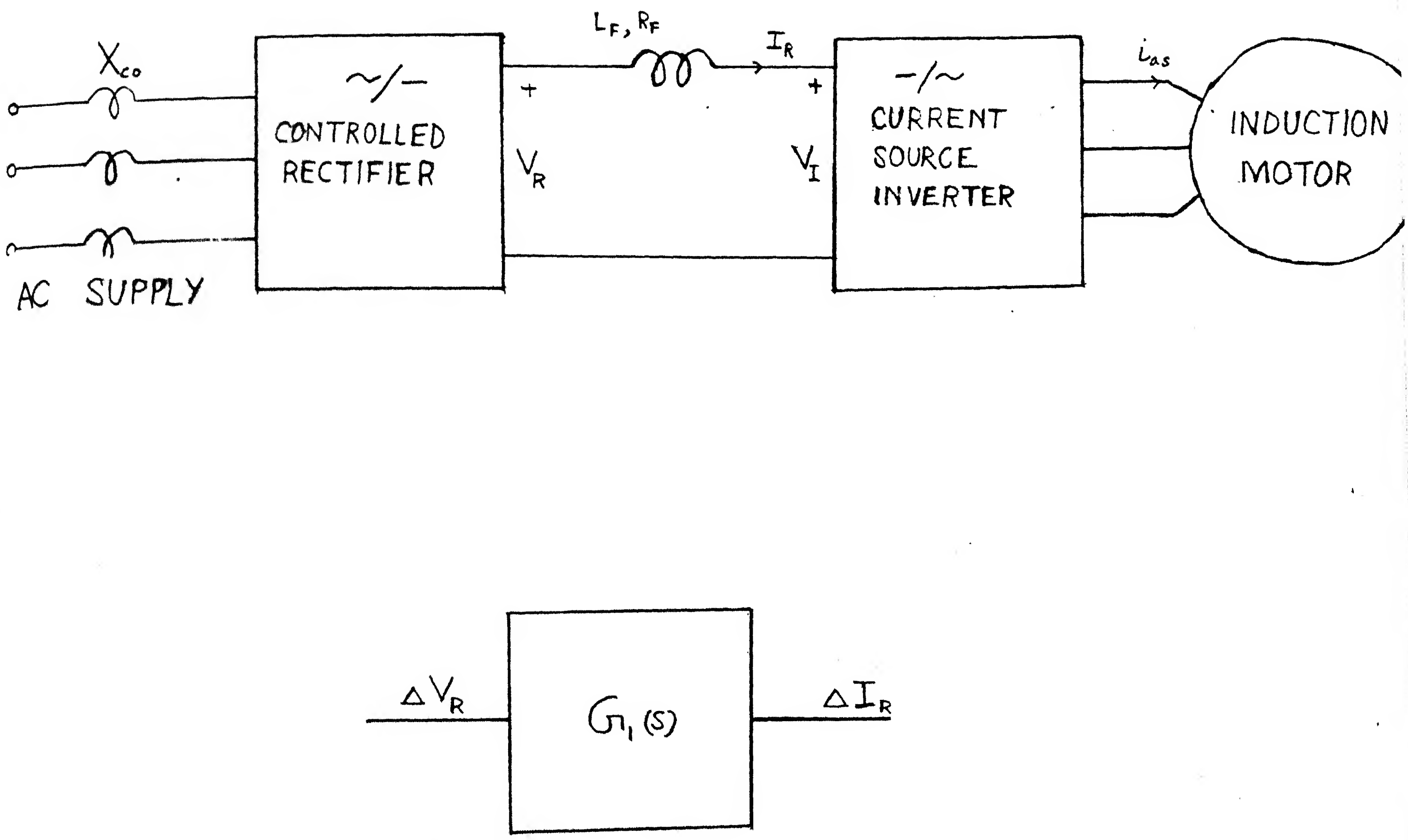
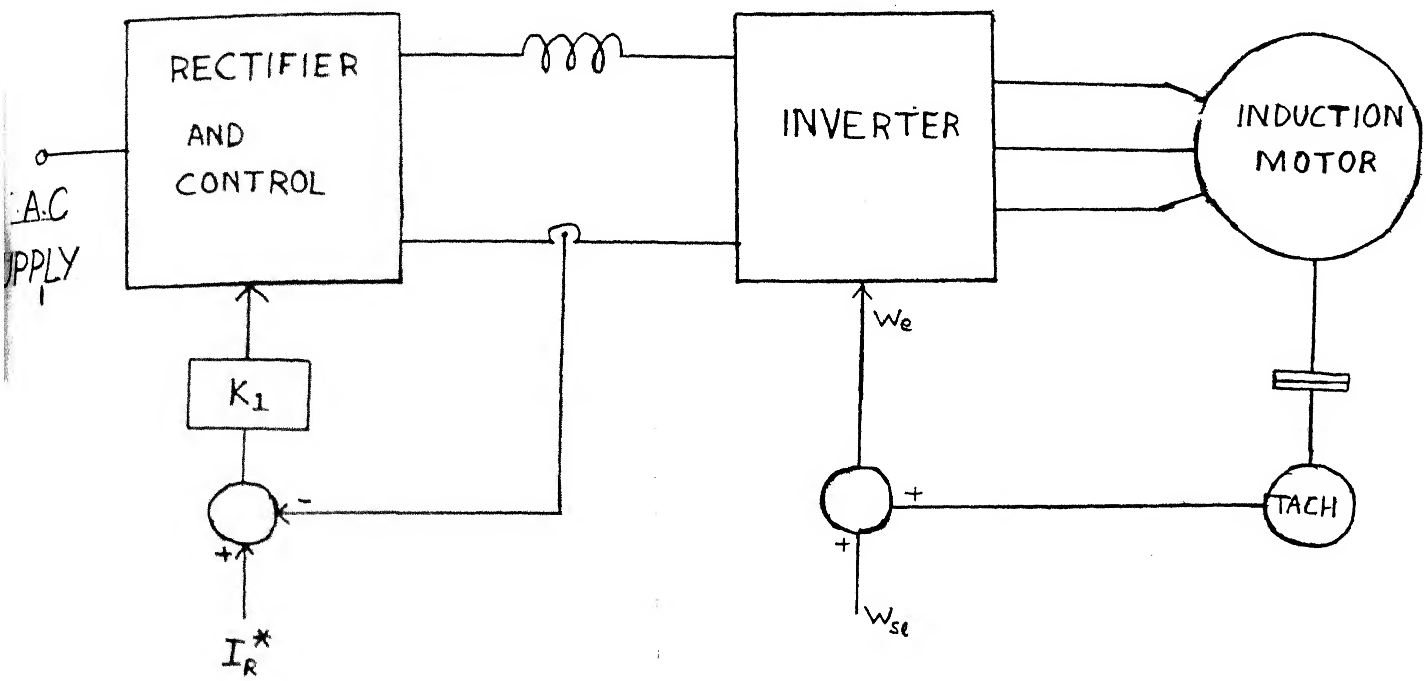


Fig. 4.5 Open Loop System



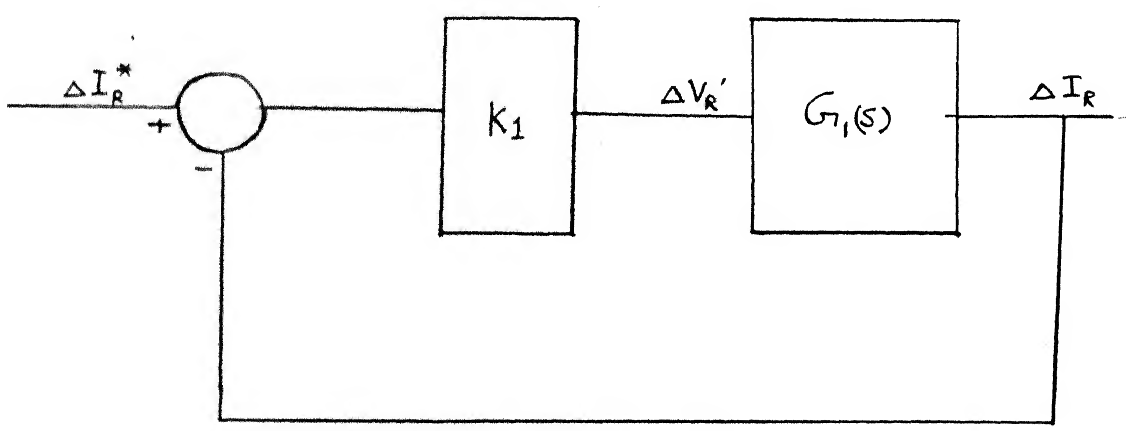


Fig. 4.6 Independent current and slip frequency control using proportional controller.

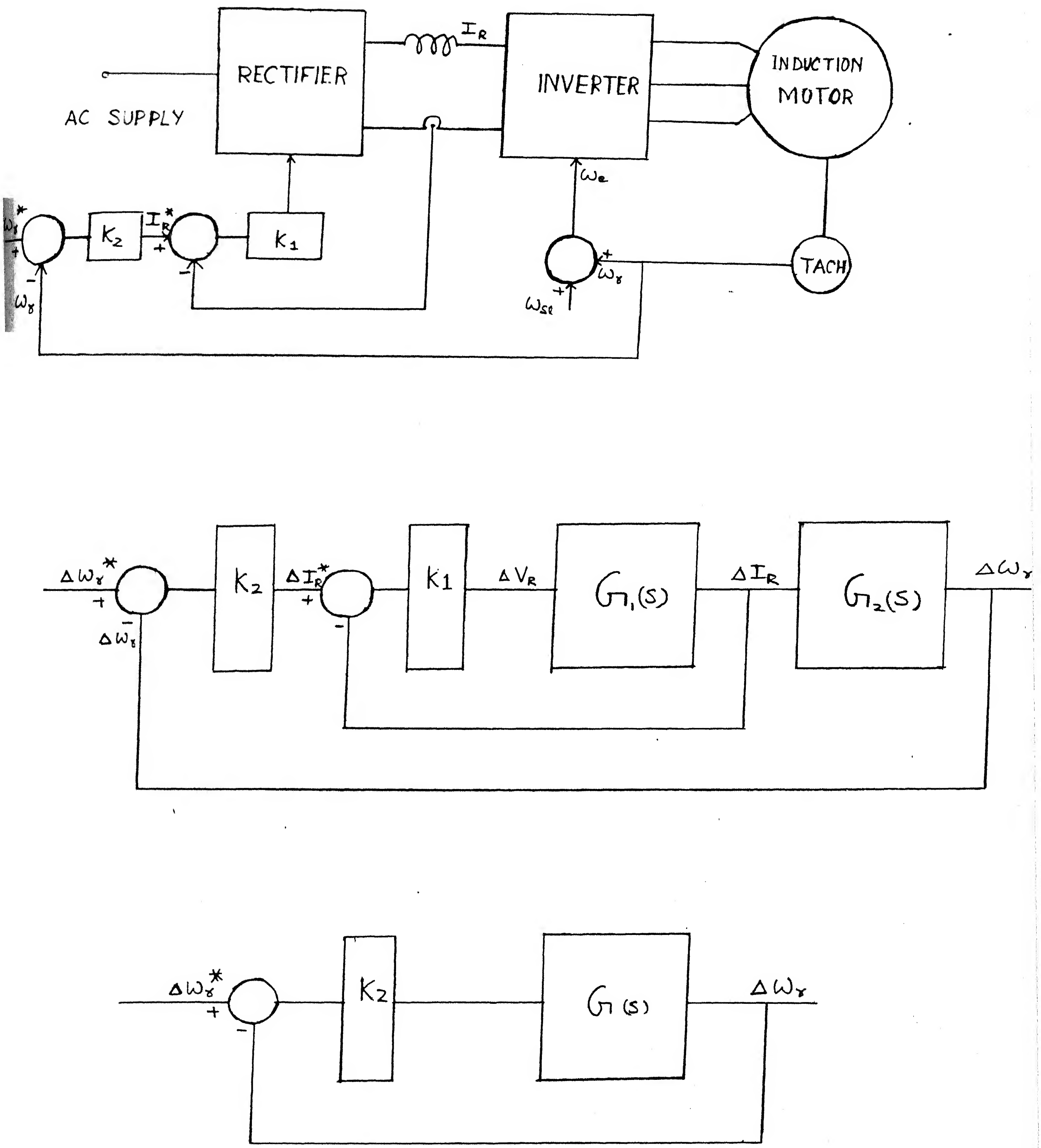


Fig. 4.7 Independent speed and slip frequency control using proportional controller.

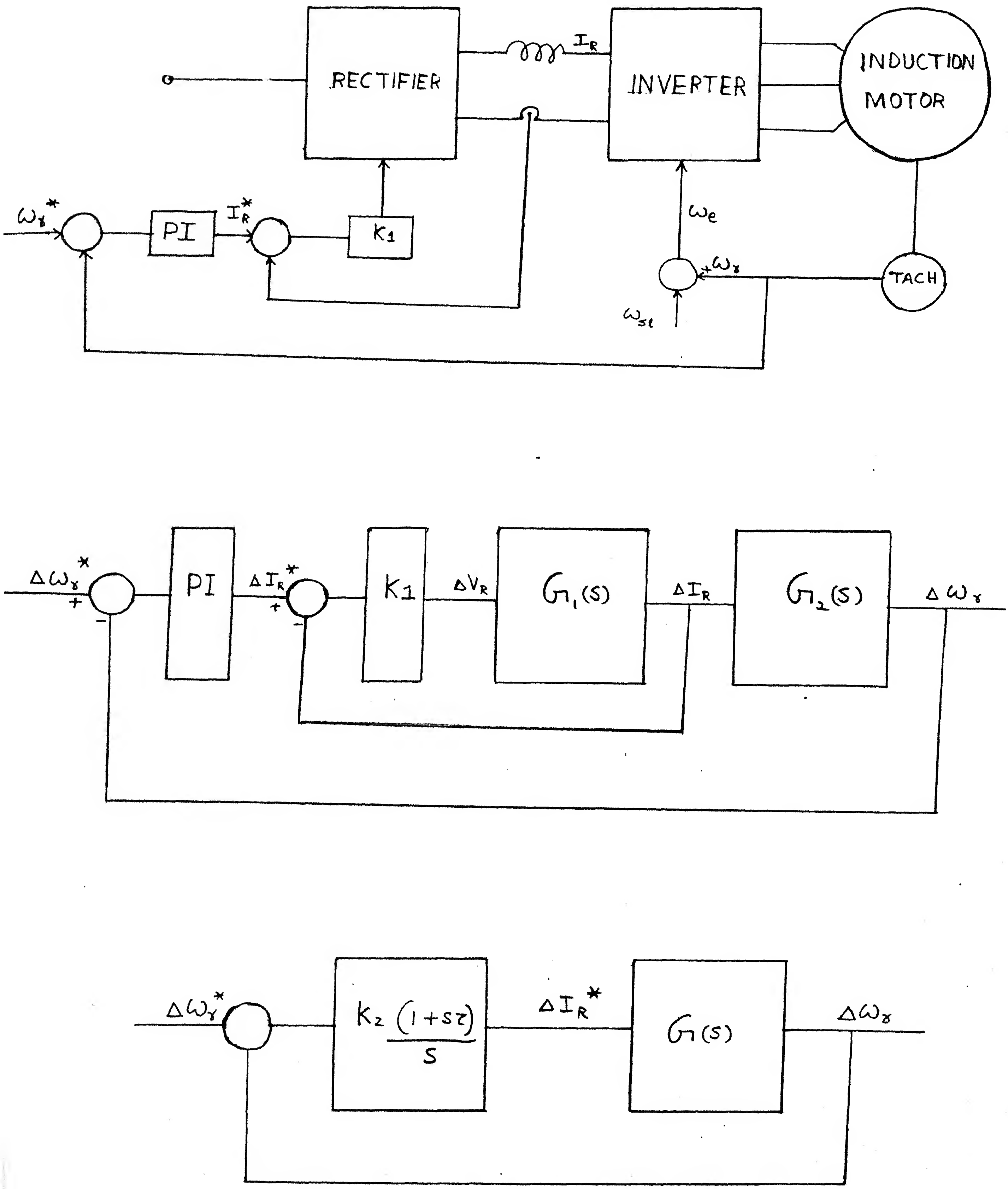


Fig. 4.8 Independent speed and slip frequency control using proportional plus integral controller.

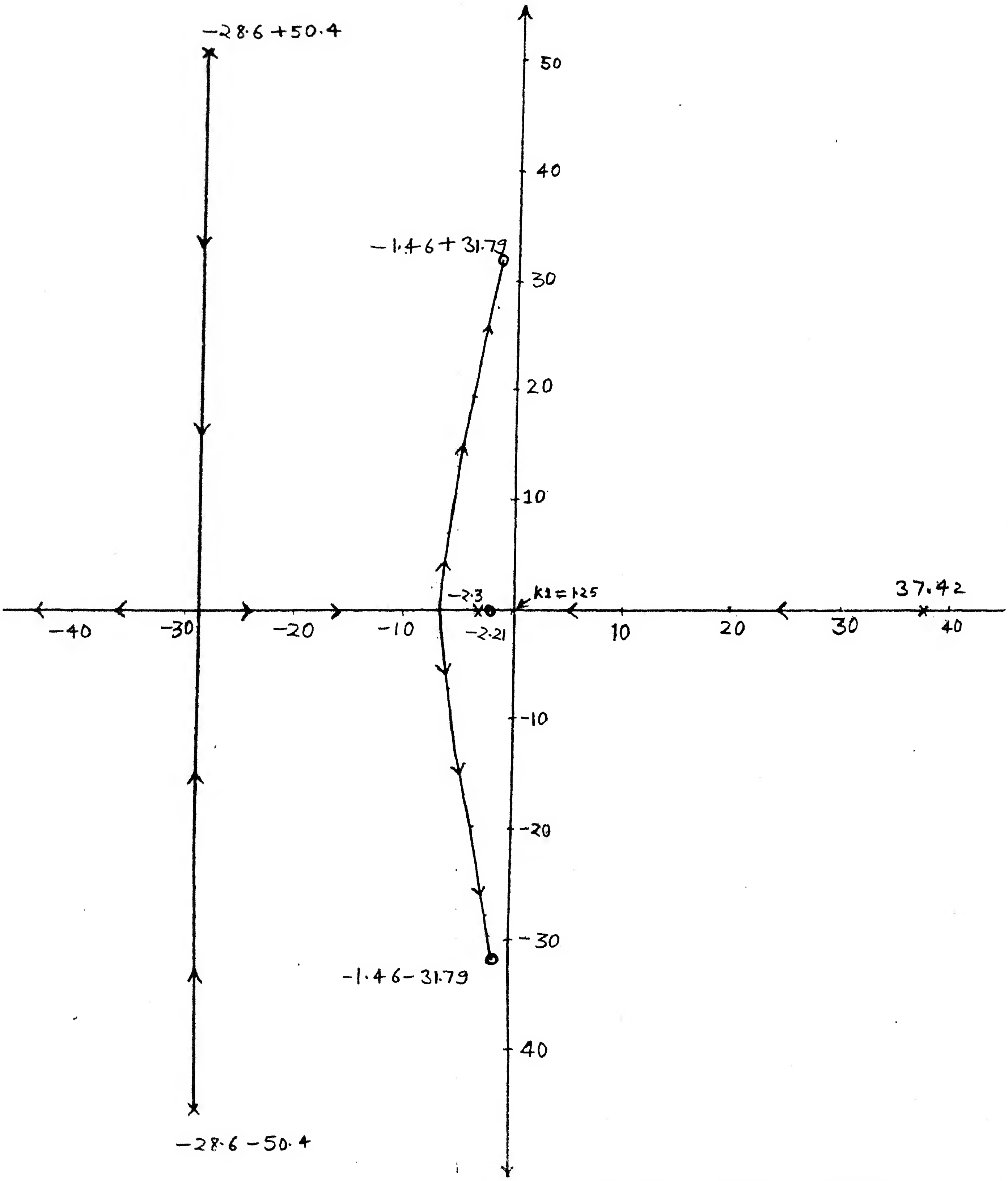


Fig. 4.9 Root locus plot for $\Delta I_R'/\Delta V_R'$, slip = 0.003, I_R = 60A; f = 50 Hz.

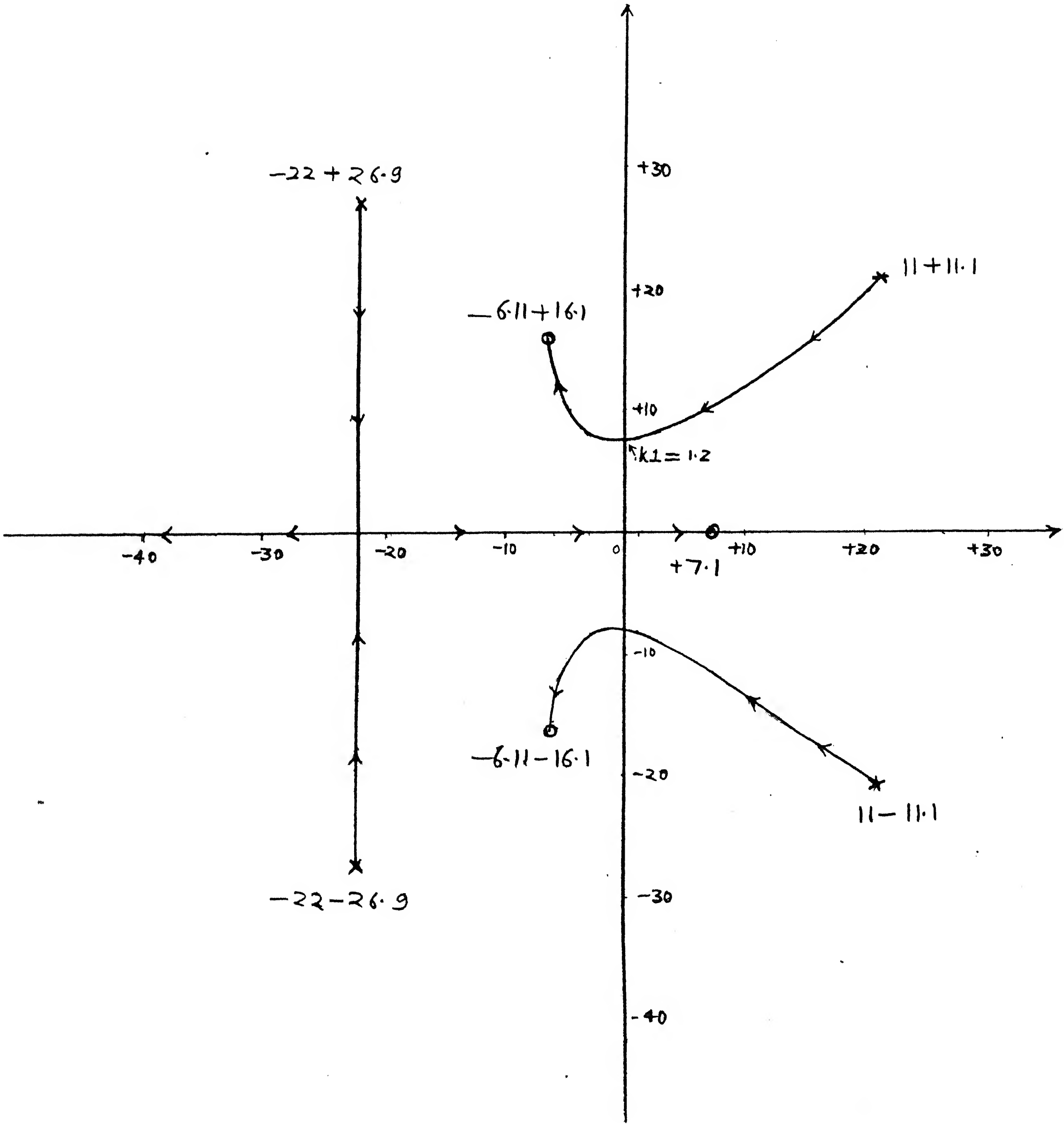
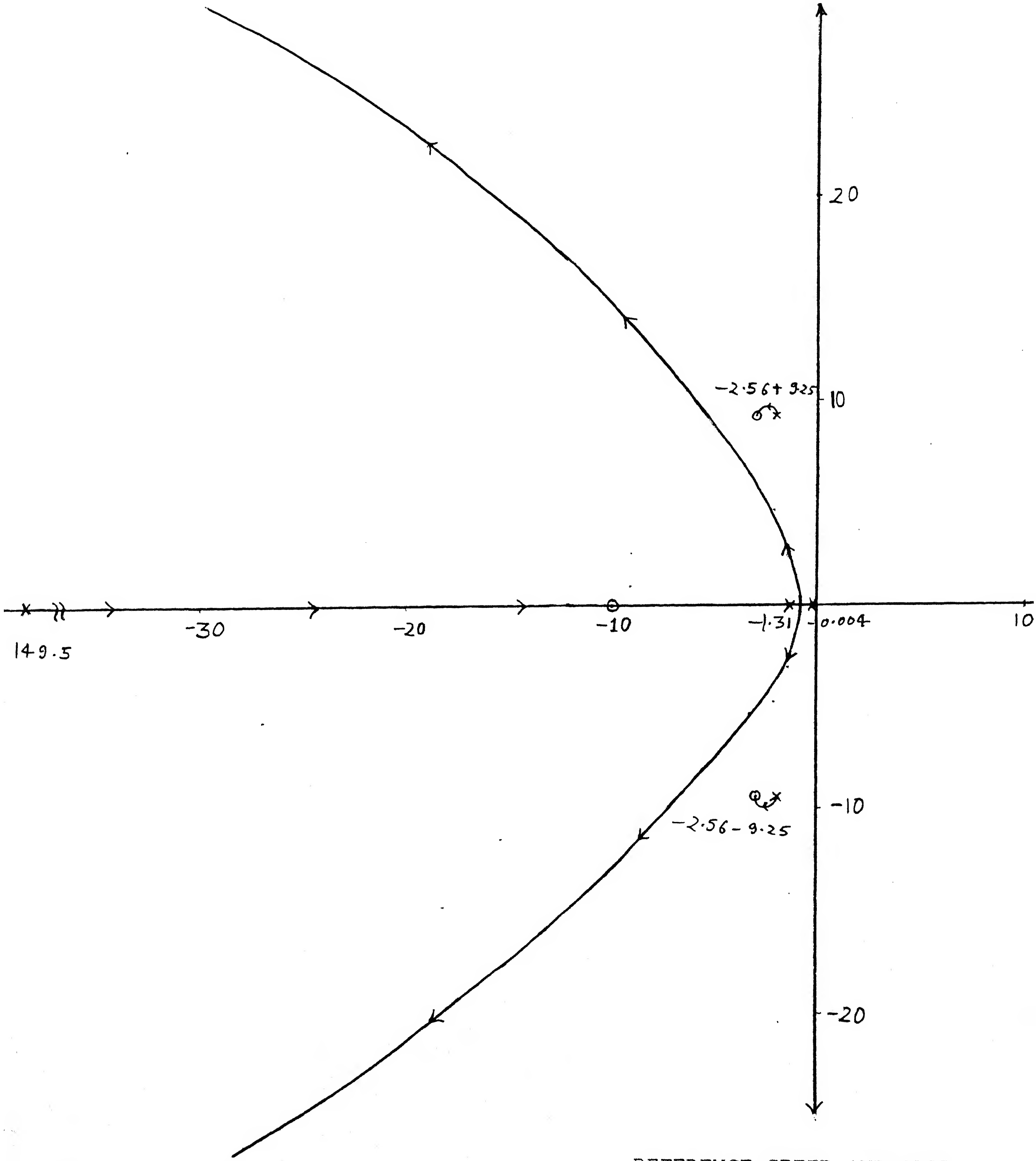


Fig. 4.10 Root locus plot for $\Delta I_R'/\Delta V_R'$; slip = 0.02 I_R = 60A; f = 50 Hz.



REFERENCE SPEED AND SLIP FREQUENCY CONTROL

Fig. 4.12: Root locus plot for $\Delta\omega_r/\Delta\omega_r^*$; slip = 0.02
I_D = 60A; K_1 = 1.3, τ = 0.1

CHAPTER 5

CONCLUSION

The steady-state characteristics of an induction motor fed with the current source inverter differ considerably from those for the same motor fed with the voltage source inverter. It was shown than current source inverter fed induction motor has certain advantages over the voltage source inverter fed induction motor.

The feasibility of developing controlled current induction motor drives using transfer function techniques has been studied. A dynamic linearized model was used as the basis of the transient response study. Open-loop operation is statically unstable for negative sloped portion and dynamically unstable for all operating points of the steady-state characteristic.

A systematic study of several controllers in a current source inverter fed induction motor drive and their effects on the dynamic response and stability of the system has been done in the current work reported in this thesis.

It has also been shown, that, independent current and slip frequency control is capable of stabilizing the drive system for all operating points. The drive system using speed and slip control is stable for all values gain for a given

frequency. The improvement in transient response was observed with closed loop operation compare to that of open loop operation.

It was shown that the system may or may not be stable for various values of gain and use of adaptive controller was suggested. There exist essentially two approaches, namely identification and control (which is mainly digital) and the other is model reference adaptive control (which can be analog or digital). The main problem in identification and control is, that, one has to do on line identification and drive systems are not all that slow to allow this kind of control. However, work is to be done in this area. In model reference adaptive control one changes the controller parameters of the actual system in such a way that the system behaviour conforms to the reference model behaviour. We do not see simple solutions in this case. However, this area needs to be explored.

In the present work, we developed a broad base for analysing controlled current inverter fed induction motor. However, we could analyse the stability and transient response for independent current and slip control. The same analysis can be extended to flux control as well as to field oriented

control. The model developed can be used to determine stability region in the parameter space. Use of adaptive control viz. identification and control or model reference adaptive control should be studied.

equations (3.2), (3.3) and (3.4) into (AI.1), and again substituting the resulting equations into (AI.2), the fundamental components i_{qs1}, i_{ds1}, and the nth harmonic components i_{qsn}, i_{dsn} are described as

$$i_{qs1} = \frac{2\sqrt{3}}{\pi} I_R$$

$$i_{ds1} = 0 \tag{AI.3}$$

$$i_{qsn} = \begin{cases} \frac{1}{n}\frac{2\sqrt{3}}{\pi} I_R \cos(n+1)\omega t, & n=5,11,\ldots,. \\ \frac{1}{n}\frac{2\sqrt{3}}{\pi} I_R \cos(n-1)\omega t, & n=7,13,\ldots, \end{cases} \tag{AI.4}$$

$$i_{dsn} = \begin{cases} \frac{1}{n}\frac{2\sqrt{3}}{\pi} I_R \sin(n+1)\omega t, & n=5,11,\ldots, \\ \frac{1}{n}\frac{2\sqrt{3}}{\pi} I_R \sin(n-1)\omega t, & n=7,13,\ldots, \end{cases} \tag{AI.5}$$

From (AI.4) - (AI.5), we get eqns. (3.37) and (3.38].

APPENDIX II

State-space representation of the system is represented in the state-space form as,

$$\dot{\underline{x}} = A\underline{x} + B\underline{x}$$

$$\underline{y} = C\underline{x}$$

Assuming zero initial conditions, we get

$$T(s) = \frac{Y(s)}{U(s)} = C(SI-A)^{-1} B$$

$$T(s) = \frac{\beta_{n-1}S^{n-1} + \dots \beta_1 S + \beta_0}{S^n + \alpha_{n-1}S^{n-1} + \dots \alpha_1 S + \alpha_0}$$

where β_i's are the coefficients of the numerator polynomial and α_i's are the coefficients of the denominator polynomial.

Consider the constant nxn matrix A with characteristic polynomial.

$$\det(SI-A) = S^n + \alpha_{n-1} S^{n-1} + \dots \alpha_1 S + \alpha_0$$

Then the resolvent of A can be written as

$$(SI-A)^{-1} = \frac{1}{\det(SI-A)} \sum_{i=1}^{n} S^{i-1} R_i$$

where the matrices R_i are given by

$$R_i = \sum_{i=1}^{n} \alpha_i A^{j-i}; \ i = 1,2,\dots,n$$

with $\alpha_n = 1$. The coefficients α_i and the matrices $R_i, i=1,2,\ldots n$ can be obtained through the following algorithms set

$$\alpha_n = 1, \quad R_n = 1$$

then,

$$\alpha_{n-k} = \frac{-1}{K} \operatorname{tr} (AR_{n-k+1})$$

$$R_{n-k} = \alpha_{n-k} I + AR_{n-k+1}$$

$$\beta_{n-k} = C\, R_{n-k} B \qquad \text{[By Tuel and Rane]}$$

for $K = 1,2,\ldots n$, for $K = n$, we have $R_o = 0$

where $\operatorname{tr}(M) = \sum_{i=1}^{n} M_{ii}$.

This algorithm is known as Leverrier's algorithm. It is also as Sourian's method or Faddeeva's method. The fact that $R_o = 0$ can be used as a numerical check. The algorithm is very convenient for a digital computer. The algorithm is relatively sensitive to round-off errors, and double precision is usually employed in the computations.

APPENDIX III

Name plate motor data	Motor and filter parameters at f = 60 Hz.
18 KW	$r_s = 0.0788\ \Omega$
4-pole	$r_r' = 0.0408\ \Omega$
3-phase Y-connected	$x_s = 5.7518\ \Omega$
$\omega_b = 377$ rad/sec	$x_r' = 6.0028\ \Omega$
$J_{Total} = 0.31\ Kg\text{-}m^2$	$x_m = 5.54\ \Omega$
$V_{rated} = 230V$ rms	$X_F = 5.50\ \Omega$
$I_{rated} = 64A$ rms	$R_F = 0.091\ \Omega$

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[27]

APPENDIX IV

```
C
C     ****************************************************************
C     THIS PROGRAM SEES THE TRANSFER FUNCTIONS IR/IR*,WR/WSL,IR/VR
C     WITH INDEPENDENT CURRENT AND FREQUENCY CONTROL
C     IT ALSO DETERMINES THE POLES AND ZEROES OF THE
C     ABOVE TRANSFER FUNCTIONS.
C     ****************************************************************
      DIMENSION A(1,4),WKSPCE(4),E(4,4),G(4,1),D(4,1)
      DIMENSION RR(4),RI(4),AA(4,4),BB(4,1),B(4,1)
      DIMENSION Z(1),INTEGE(4),C(1,4),NUMR(5),DEN(5)
      DIMENSION RRZ(4),IMZ(4),RZ(4),IZ(4),H(4,4)
      READ L1
      OPEN(UNIT=40,DEVICE='DSK',FILE='INPUT.DAT')
      OPEN(UNIT=6,DEVICE='DSK',FILE='ERROR.DAT')
      OPEN(UNIT=41,DEVICE='DSK',FILE='OUTPUT.DAT')
      READ(40,*) ((E(IA,N),N=1,4),IA=1,4)
      READ(40,*) ((G(IB,M),IB=1,4),M=1,1)
      IA=4;IB=4;IC=1;J=4
C     FO=50;CIR=6;S=0.03
      READ(05,*) FO,S,CIR,L1
C     READ(05,*) L1
      WRITE(05,*) FO,S,CIR,L1
      WRITE(41,97)
97    FORMAT(1X,///////)
      WRITE(41,95)
95    FORMAT(10X,'*********************************************',/)
      WRITE(41,94)
94    FORMAT(10X,'THE TRANSFER FUNCTION IR/IR* USING P CONTROLLER',/)
      WRITE(41,96)
96    FORMAT(10X,'*********************************************',/)
      WRITE(41,92)
92    FORMAT(10X,'FREQUENCY',4X,'SLIP',6X,'CURRENT',6X,'GAIN',/)
      WRITE(41,93) FO,S,CIR,L1
93    FORMAT(5X,4F12.4,/)
      CQS=1.10266*CIR;  P=4.0;WB=60.0*6.2832;WE=6.2832*FO;RJ=0.31
      RS=0.0788;R2=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB
      FL=5.5/WB;RF=0.091;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1
      R1=RS+RF1;CL=(F*RL-CM*CM) ;WR=WE-S*WE;WSL=WE-WR
      E(1,3)=CM*WE; E(2,3)=RL*S*WE
      E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*CQS
      G(1,1)=-R1*CQS; G(3,1)=CM*S*CQS*WE
C     *******THE EQUATION IS [A11][X]=[B]*******************
      WRITE(41,12)
12    FORMAT(20X,'THE MATRIX [A11] IS',/)
      WRITE(41,13)((E(IA,N),N=1,4),IA=1,4)
13    FORMAT(10X,4F10.4/)
      WRITE(41,14)
14    FORMAT(10X,'THE MATRIX [B] IS',/)
      WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
15    FORMAT(10X,F10.4,/)
C     ********** FINDS STEADY STATE OPERATING POINT *************
      WRITE(41,19)
19    FORMAT(15X,'THE STEADY STATE OPERATING POINT IS')
      CALL F04AEF(E,4,G,4,4,1,D,4,WKSPCE,AA,4,BB,4,0)
      D(1,1)=1.654*D(1,1)
      WRITE(41,16)
16    FORMAT(4X,'VOLTAGE',4X,'IQRO',8X,'IDRO',5X,'TORQUE',/)
      WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
17    FORMAT(1X,4F10.2)
      R=R1+L1
C     R=R1
      A(1,1)=-(RL*R)/CL;A(1,2)=CM*R2/CL;A(1,3)=-CM*RL*WR/CL
      A(1,4)=-CM*RL*D(3,1)/CL;A(2,1)=CM*R/CL;A(2,2)=-F*R2/CL
      A(2,3)=RL*F*WR/CL-WE;A(2,4)=(RL*F*D(3,1)/CL)
      A(3,1)=CM*WSL/RL;A(3,2)=WSL;A(3,3)=-R2/RL
      A(3,4)=-(CM*CQS+RL*D(2,1))/RL
      A(4,1)=3*P*P*CM*D(3,1)/(8*RJ);A(4,2)=0
      A(4,3)=(3*P*P*CM*CQS)/(8*RJ);A(4,4)=0
      DO 3 I=1,4
      DO 4 J=1,4
      H(I,J)=A(I,J)
4     CONTINUE
3     CONTINUE
      WRITE(41,71)
71    FORMAT(20X,'THE MATRIX [A] IS',/)
      WRITE(41,72) ((A(M,K),K=1,4),M=1,4)
72    FORMAT(10X,4F10.4,/)
      B(1,1)=L1*RL/CL;B(2,1)=-L1*CM/CL;B(3,1)=0;B(4,1)=0
C     B(1,1)=RL/CL;B(2,1)=-CM/CL;B(3,1)=0;B(4,1)=0
C     B(1,1)=0;B(2,1)=0;B(3,1)=(CM*CQS+RL*D(2,1))/RL;B(4,1)=0
      WRITE(41,21)
21    FORMAT(20X,'THE MATRIX [B] IS',/)
```

```
C(1,1)=0;C(1,2)=0;C(1,3)=0;C(1,4)=1
C(1,1)=1;C(1,2)=0;C(1,3)=0;C(1,4)=0
WRITE(41,23)
FORMAT(20X,'THE MATRIX [C] IS',/)
WRITE(41,21) ((C(N,K),K=1,4),N=1,1)
FORMAT(20X,'['4F4,']',/)
CALL SSP2TF(A,4,B,4,C,1,4,NUMR,DEN,INUM,IFAIL)
WRITE(41,31)
FORMAT(10X,'THE COEFICIENTS OF THE NUM IN TRANSFER FUNC',/)
WRITE(41,11)(NUMR(I),I=1,INUM)
WRITE(41,32)
FORMAT(10X,'THE COEFICIENT OF THE DEN IN THE TRANSFER FUNC',/)
WRITE(41,11)(DEN(I),I=1,5)
FORMAT(/(1X,5F15.6))
CALL F02AFF(A,4,4,RR,RI,INTEGE,0)
WRITE(41,81)
FORMAT(10X,'THE POLES OF THE MATRIX [A] ARE',/)
WRITE(41,83) (RR(N),RI(N),N=1,4)
FORMAT(10X,2F16.4)
WRITE(41,98)
FORMAT(1X,2(///////))
CALL C02AEF(DEN,5,REZ,IMZ,TOL,0)
WRITE(41,75)
FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE',/)
WRITE(41,76) (REZ(N),IMZ(N),N=1,4)
FORMAT(10X,2F16.4)
CALL C02AEF(NUMR,INUM,RZ,IZ,TOL,0)
WRITE(41,77)
FORMAT(10X,'THE ZEROES OF THE TRANSFER FUNCTION ARE',/)
WRITE(41,78) (RZ(I),IZ(I),I=1,3)
FORMAT(10X,2F16.4)
STOP
END
SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
REAL NUMR(5),DEN(5)
REAL A(4,4),B(4,1),C(1,4),TMP1(4,4),TMP2(1,1),R(4,4)
DATA EPS/0.000001/
IFAIL = 1
IF( N .LE. 0 ) RETURN
IFAIL = 2
DO 10 I = 1,N
  IF(B(I,1) .NE. 0.0) GOTO 36
CONTINUE
RETURN
DO 20 I = 1,N
DO 20 J = 1,N
  R(I,J) = 0.0
  R(I,I) = 1.0
CONTINUE
DEN(1) = 1.0
DO 50 K = 1,N
CALL F01CKF(TMP1,R,B,4,4,4,Z,1,1,0)
CALL F01CKF(TMP2,C,TMP1,1,1,4,Z,1,1,0)
  NUMR(K) = TMP2(1,1)
CALL F01CKF(TMP1,A,R,4,4,4,Z,1,1,0)
  ALPHAK = -TRACE(TMP1,4,4)/K
  DEN(K+1) = ALPHAK
  DO 40 I = 1,N
    DO 30 J = 1,N
      R(I,J) = TMP1(I,J)
IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
    CONTINUE
  CONTINUE
CONTINUE
DO 60 I = 1,N
  IF(ABS(NUMR(I)) .GT. EPS ) GOTO 22
CONTINUE
INUM = 0
DO 70 J = I,N
  INUM = INUM + 1
  NUMR(INUM) = NUMR(J)
CONTINUE
RETURN
END
```

```
DO 56 I=1,3
TRACE=TRACE+A(I,I)
CONTINUE
RETURN
END
```

```
*****************************************************************
THE TRANSFER FUNCTION IR/IR* USING P CONTROLLER
*****************************************************************
FREQUENCY      SLIP        CURRENT        GAIN
50.0000        0.0230      60.0000        1.3000
            THE MATRIX [A11] IS
   -1.0000     0.0000      4.6167     0.0000
    0.0000     0.0408      0.0150     0.0000
    0.0000    -0.0150      0.0408     0.0000
    0.0000     0.0000      2.9167    -1.0000
THE MATRIX [B] IS
   -8.5144
    0.0000
    0.9163
    0.0000
          THE STEADY STATE OPERATING POINT IS
VOLTAGE      IQRO         IDRO        TORQUE
165.14       -7.28        19.78       57.70
              THE MATRIX [A] IS
        -147.3790         3.8843        -174.8097       -29.9881
         136.0165        -6.1472         137.2607        47.4583
           0.8698         0.9425          -2.5623       -53.7826
           5.6266         0.0000          18.8174         0.0000
              THE MATRIX [B] IS
         134.1032
        -123.7642
           0.0000
           0.0000
              THE MATRIX [C] IS
              [ 1.  0.  0.  0.]
     THE COEFICIENTS OF THE NUM IN TRANSFER FUNC
134.103240     687.238860   136718.730000   300711.450000
     THE COEFICIENTS OF THE DEN IN THE TRANSFER FUNC
1.000000      155.038500    1952.691900    13935.023000    11166.964000
     THE POLES OF THE MATRIX [A] ARE
            -144.1214            0.0000
              -5.5[illegible]7            0.0000
              -5.[illegible]292            7.0364
              -5.[illegible]292           -7.0364
```

THE POLES OF THE TRANSFER FUNCTION ARE

-133.1214	0.0000
-5.0292	-7.0364
-5.0292	7.0364
-0.9387	0.0000

THE ZEROES OF THE TRANSFER FUNCTION ARE

-1.3556	-31.7953
-1.3556	31.7953
-2.2135	0.0000

```
C         ***************************************************************
C         THIS PROGRAM GETS THE TRANSFER FUNCTIONS IR/IR*,WR/WSL,IR/VR
C         WITH INDEPENDENT CURRENT AND SLIP FREQUENCY CONTROL
C         IT ALSO DETERMINES THE POLES AND ZEROES OF THE
C         ABOVE TRANSFER FUNCTIONS.
C         ***************************************************************
          DIMENSION A(4,4),WKSPCE(4),E(4,4),G(4,1),D(4,1)
          DIMENSION RR(4),RI(4),AA(4,4),BB(4,1),B(4,1)
          DIMENSION Z(1),INTEGE(4),C(1,4),NUMR(5),DEN(5)
          DIMENSION REZ(4),IMZ(4),RZ(4),IZ(4),H(4,4)
          REAL L1
          OPEN(UNIT=40,DEVICE='DSK',FILE='INPUT.DAT')
          OPEN(UNIT=6,DEVICE='DSK',FILE='ERROR.DAT')
          OPEN(UNIT=41,DEVICE='DSK',FILE='OUTPUT.DAT')
          READ(40,*) ((E(IA,N),N=1,4),IA=1,4)
          READ(40,*) ((G(IB,M),IB=1,4),M=1,1)
          IA=4;IB=4;IC=1;N=4
          FQ=50;CIR=60;S=0.003
          READ(05,*) L1
C         READ(05,*) FQ,S,CIR,L1
          WRITE(05,*) FQ,S,CIR,L1
          WRITE(41,97)
 97       FORMAT(1X,///////)
          WRITE(41,95)
 95       FORMAT(10X,'*********************************************',/
          WRITE(41,94)
 94       FORMAT(10X,'THE TRANSFER FUNCTION IR/IR* USING P CONTROLLER',/)
          WRITE(41,96)
 96       FORMAT(10X,'*********************************************',/
          WRITE(41,92)
 92       FORMAT(10X,'FREQUENCY',4X,'SLIP',6X,'CURRENT',6X,'GAIN',/)
          WRITE(41,93) FQ,S,CIR,L1
 93       FORMAT(5X,4F12.4,/)
          COS=1.10266*CIR;  P=4.0;WB=60.0*6.2832;WE=6.2832*FQ;RJ=0.31
          RS=0.0788;R2=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB
          FL=5.5/WB;RF=0.091;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1
          R1=RS+RF1;CL=(F*RL-CM*CM) ;WR=WE-S*WE;WSL=WE-WR
          E(1,3)=CM*WE; E(2,3)=RL*S*WE
          E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*COS
          G(1,1)=-R1*COS; G(3,1)=CM*S*COS*WE
C         *******THE EQUATION IS [A11][X]=[B]*******************
          WRITE(41,12)
 12       FORMAT(20X,'THE MATRIX [A11] IS',/)
          WRITE(41,13)((E(IA,N),N=1,4),IA=1,4)
 13       FORMAT(10X,4F10.4/)
          WRITE(41,14)
 14       FORMAT(10X,'THE MATRIX [B] IS',/)
          WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
 15       FORMAT(10X,F10.4,/)
C         ********** FINDS STEADY STATE OPERATING POINT *************
          WRITE(41,19)
 19       FORMAT(15X,'THE STEADY STATE OPERATING POINT IS')
          CALL F04AEF(E,4,G,4,4,1,D,4,WKSPCE,AA,4,BB,4,0)
          D(1,1)=1.654*D(1,1)
          WRITE(41,16)
 16       FORMAT(4X,'VOLTAGE',4X,'IQRO',8X,'IDRO',5X,'TORQUE',/)
          WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
 17       FORMAT(1X,4F10.2)
          R=R1+L1
C         R=R1
          A(1,1)=-(RL*R)/CL;A(1,2)=CM*R2/CL;A(1,3)=-CM*RL*WR/CL
          A(1,4)=-CM*RL*D(3,1)/CL;A(2,1)=CM*R/CL;A(2,2)=-F*R2/CL
          A(2,3)=RL*F*WR/CL-WE;A(2,4)=CM*CM*D(3,1)/CL
          A(3,1)=CM*WSL/RL;A(3,2)=WSL;A(3,3)=-R2/RL
          A(3,4)=0
          A(4,1)=3*P*P*CM*D(3,1)/(8*RJ);A(4,2)=0
          A(4,3)=(3*P*P*CM*COS)/(8*RJ);A(4,4)=0
          DO 3 I=1,N
          DO 4 J=1,N
          H(I,J)=A(I,J)
 4        CONTINUE
 3        CONTINUE
          WRITE(41,73)
 73       FORMAT(20X,'THE MATRIX [A] IS',/)
          WRITE(41,74) ((A(N,K),K=1,4),N=1,4)
 74       FORMAT(10X,4F10.4,/)
```

```
      B(1,1)=L1*RL/CL;B(2,1)=-L1*CM/CL;B(3,1)=0;B(4,1)=0
C     B(1,1)=RL/CL;B(2,1)=-CM/CL;B(3,1)=0;B(4,1)=0
C     B(1,1)=0;B(2,1)=-D(3,1);B(3,1)=(CM*COS+RL*D(2,1))/RL;B(4,1)=0
      WRITE(41,21)
21    FORMAT(20X,'THE MATRIX [B] IS',/)
      WRITE(41,38) ((B(N,K),K=1,1),N=1,4)
38    FORMAT(10X,F16.4,/)
      C(1,1)=1;C(1,2)=0;C(1,3)=0;C(1,4)=0
C     C(1,1)=0;C(1,2)=0;C(1,3)=0;C(1,4)=1
      WRITE(41,23)
23    FORMAT(20X,'THE MATRIX [C] IS',/)
      WRITE(41,24) ((C(N,K),K=1,4),N=1,1)
24    FORMAT(20X,'[',4F4,']',/)
      CALL SSP2TF(A,4,B,4,C,1,4,NUMR,DEN,INUM,IFAIL)
      WRITE(41,31)
31    FORMAT(10X,'THE COEFICIENTS OF THE NUM IN TRANSFER FUNC',/)
      WRITE(41,11)(NUMR(I),I=1,INUM)
      WRITE(41,32)
32    FORMAT(10X,'THE COEFICIENT OF THE DEN IN THE TRANSFER FUNC',/)
      WRITE(41,11)(DEN(I),I=1,5)
      WRITE(41,98)
98    FORMAT(1X,2(//////////))
11    FORMAT(/(1X,5F15.6))
      CALL F02AFF(H,4,4,RR,RI,INTEGE,0)
      WRITE(41,81)
81    FORMAT(10X,'THE POLES OF THE MATRIX [A] ARE',/)
      WRITE(41,83) (RR(N),RI(N),N=1,4)
83    FORMAT(10X,2F16.4)
      CALL C02AEF(DEN,5,REZ,IMZ,TOL,0)
      WRITE(41,75)
75    FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE',/)
      WRITE(41,76) (REZ(N),IMZ(N),N=1,4)
76    FORMAT(10X,2F16.4)
      CALL C02AEF(NUMR,INUM,RZ,IZ,TOL,0)
      WRITE(41,77)
77    FORMAT(10X,'THE ZEROES OF THE TRANSFER FUNCTION ARE',/)
      WRITE(41,78) (RZ(I),IZ(I),I=1,3)
78    FORMAT(10X,2F16.4)
      STOP
      END
C     ********************************************************
C     THIS SUBROUTINE DETERMINES THE COEFICIENTS OF NUM & DEN
C     OF THE TRANSFER FUNCTION.
C     ********************************************************
      SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
      REAL NUMR(5),DEN(5)
      REAL A(4,4),B(4,1),C(1,4),TMP1(4,4),TMP2(1,1),R(4,4)
      DATA EPS/0.000001/
      IFAIL = 1
      IF( N .LE. 0 ) RETURN
      IFAIL = 2
      DO 10 I = 1,N
        IF(B(I,1) .NE. 0.0) GOTO 36
10    CONTINUE
      RETURN
36    DO 20 I = 1,N
      DO 20 J = 1,N
        R(I,J) = 0.0
        R(I,I) = 1.0
20    CONTINUE
      DEN(1) = 1.0
      DO 50 K = 1,N
      CALL F01CKF(TMP1,R,B,4,1,4,Z,1,1,0)
      CALL F01CKF(TMP2,C,TMP1,1,1,4,Z,1,1,0)
        NUMR(K) = TMP2(1,1)
      CALL F01CKF(TMP1,A,R,4,4,4,Z,1,1,0)
        ALPHAK = -TRACE(TMP1,4,4)/K
        DEN(K+1) = ALPHAK
        DO 40 I = 1,N
          DO 30 J = 1,N
            R(I,J) = TMP1(I,J)
      IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
30          CONTINUE
40        CONTINUE
50    CONTINUE
```

```
      DO 60 I = 1,N
        IF(ABS(NUMR(I)) .GT. EPS ) GOTO 22
60    CONTINUE
22    INUM = 0
      DO 70 J = I,N
        INUM = INUM + 1
        NUMR(INUM) = NUMR(J)
70    CONTINUE
      RETURN
      END
      FUNCTION TRACE(A,IA,N)
      REAL A(4,4)
      TRACE=0.0
      DO 56 I=1,N
      TRACE=TRACE+A(I,I)
56    CONTINUE
      RETURN
      END
```

****

THE TRANSFER FUNCTION IR/IR* USING P CONTROLLER

****

FREQUENCY	SLIP	CURRENT	GAIN
50.0000	0.0030	60.0000	1.3000

THE MATRIX [A11] IS

-1.0000	0.0000	4.6167	0.0000
0.0000	0.0408	0.0150	0.0000
0.0000	-0.0150	0.0408	0.0000
0.0000	0.0000	2.9167	-1.0000

THE MATRIX [B] IS

-8.5144

0.0000

0.9163

0.0000

THE STEADY STATE OPERATING POINT IS

VOLTAGE	IQRO	IDRO	TORQUE
165.14	-7.28	19.78	57.70

THE MATRIX [A] IS

-147.3790	3.8843	-474.8097	-29.9881
136.0165	-6.1472	437.2607	27.6761
0.8698	0.9425	-2.5623	0.0000
5.6266	0.0000	18.8174	0.0000

THE MATRIX [B] IS

134.1032

-123.7642

0.0000

0.0000

THE MATRIX [C] IS

[1. 0. 0. 0.]

THE COEFICIENTS OF THE NUM IN TRANSFER FUNC

134.103240 687.238860 999.591420 0.060263

THE COEFICIENT OF THE DEN IN THE TRANSFER FUNC

1.000000 158.088500 940.642240 3024.664200 2515.404000

```
THE POLES OF THE MATRIX [A] ARE

     -149.9492          0.0000
       -2.4791          2.8386
       -2.4791         -2.8386
       -1.1810          0.0000
THE POLES OF THE TRANSFER FUNCTION ARE

     -149.9492          0.0000
       -2.4791         -2.8386
       -2.4791          2.8386
       -1.1811          0.0000
THE ZEROES OF THE TRANSFER FUNCTION ARE

       -2.5623         -0.9424
       -2.5623          0.9424
       -0.0001          0.0000
```

```
C         ********************************************************************
C         THIS PROGRAM GETS THE TRANSFER FUNCTIONS WR/WR* , WR/WE
C         WITH INDEPENDENT CURRENT AND FREQUENCY CONTROL USING
C         PROPORTIONAL  CONTROLLER.IT ALSO DETERMINES THE
C         POLES AND ZEROES OF THE ABOVE TRANSFER FUNCTIONS.
C         ********************************************************************
          DIMENSION A(4,4),WKSPCE(4),E(4,4),G(4,1),D(4,1)
          DIMENSION RR(4),RI(4),AA(4,4),BB(4,1),B(4,1)
          DIMENSION Z(1),INTEGE(4),C(1,4),NUMR(5),DEN(5)
          DIMENSION REZ(4),IMZ(4),RZ(4),IZ(4),H(4,4)
          REAL L1,L2
          OPEN(UNIT=40,DEVICE='DSK',FILE='INPUT.DAT')
          OPEN(UNIT=6,DEVICE='DSK',FILE='ERROR.DAT')
          OPEN(UNIT=41,DEVICE='DSK',FILE='OUTPUT.DAT')
          READ(40,*) ((E(IA,N),N=1,4),IA=1,4)
          READ(40,*) ((G(IB,M),IB=1,4),M=1,1)
          IA=4;IB=4;IC=1;N=4
C         FQ=50;CIR=60;S=0.003
          READ(05,*) FQ,S,CIR,L1,L2
C         READ(05,*) L1
          WRITE(05,*) FQ,S,CIR,L1,L2
          WRITE(41,97)
 97       FORMAT(1X,///////)
          WRITE(41,95)
 95       FORMAT(10X,'****************************************************',/
          WRITE(41,94)
 94       FORMAT(10X,'THE TRANSFER FUNCTION WR/WR* USING P CONTROLLER',/)
          WRITE(41,96)
 96       FORMAT(10X,'****************************************************',/
          WRITE(41,92)
 92       FORMAT(10X,'FREQ',6X,'SLIP',6X,'CURR',6X,'G1',6X,'G2',/)
          WRITE(41,93) FQ,S,CIR,L1,L2
 93       FORMAT(5X,5F10.4,/)
          COS=1.10266*CIR;   P=4.0;WB=60.0*6.2832;WE=6.2832*FQ;RJ=0.31
          RS=0.0788;R2=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB
          FL=5.5/WB;RF=0.091;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1
          R1=RS+RF1;CL=(F*RL-CM*CM) ;WR=WE-S*WE;WSL=WE-WR
          E(1,3)=CM*WE; E(2,3)=RL*S*WE
          E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*COS
          G(1,1)=-R1*COS; G(3,1)=CM*S*COS*WE
C         *******THE EQUATION IS [A11][X]=[B]********************
          WRITE(41,12)
 12       FORMAT(20X,'THE MATRIX [A11] IS',/)
          WRITE(41,13)((E(IA,N),N=1,4),IA=1,4)
 13       FORMAT(10X,4F10.4/)
          WRITE(41,14)
 14       FORMAT(10X,'THE MATRIX [B] IS',/)
          WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
 15       FORMAT(10X,F10.4,/)
C         *********** FINDS STEADY STATE OPERATING POINT **************
          WRITE(41,19)
 19       FORMAT(15X,'THE STEADY STATE OPERATING POINT IS')
          CALL F04AEF(E,4,G,4,4,1,D,4,WKSPCE,AA,4,BB,4,0)
          D(1,1)=1.654*D(1,1)
          WRITE(41,16)
 16       FORMAT(4X,'VOLTAGE',4X,'IQRO',8X,'IDRO',5X,'TORQUE',/)
          WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
 17       FORMAT(1X,4F10.2)
          R=R1+L1
C         R=R1
          A(1,1)=-(RL*R)/CL;A(1,2)=CM*R2/CL;A(1,3)=-CM*RL*WR/CL
          A(1,4)=-CM*RL*D(3,1)/CL-L1*RL/CL;A(2,1)=CM*R/CL;A(2,2)=-F*R2/C
          A(2,3)=RL*F*WR/CL-WE;A(2,4)=(RL*F*D(3,1)/CL)+L1*CM/CL
          A(3,1)=CM*WSL/RL;A(3,2)=WSL;A(3,3)=-R2/RL
          A(3,4)=-(CM*COS+RL*D(2,1))/RL
          A(4,1)=3*P*P*CM*D(3,1)/(8*RJ);A(4,2)=0
          A(4,3)=(3*P*P*CM*COS)/(8*RJ);A(4,4)=0
          DO 3 I=1,N
          DO 4 J=1,N
          H(I,J)=A(I,J)
 4        CONTINUE
 3        CONTINUE
          WRITE(41,73)
 73       FORMAT(20X,'THE MATRIX [A] IS',/)
          WRITE(41,74) ((A(N,K),K=1,4),N=1,4)
```

```
 74       FORMAT(10X,4F16.4,/)
          B(1,1)=L1*L2*RL/CL;B(2,1)=-L1*L2*CM/CL;B(3,1)=0;B(4,1)=0
C         B(1,1)=RL/CL;B(2,1)=-CM/CL;B(3,1)=0;B(4,1)=0
C         B(1,1)=0;B(2,1)=-D(3,1);B(3,1)=(CM*CQS+RL*D(2,1))/RL;B(4,1)=0
          WRITE(41,21)
 21       FORMAT(20X,'THE MATRIX [B] IS',/)
          WRITE(41,38) ((B(N,K),K=1,1),N=1,4)
 38       FORMAT(10X,F16.4,/)
          C(1,1)=0;C(1,2)=0;C(1,3)=0;C(1,4)=1
C         C(1,1)=1;C(1,2)=0;C(1,3)=0;C(1,4)=0
          WRITE(41,23)
 23       FORMAT(20X,'THE MATRIX [C] IS',/)
          WRITE(41,24) ((C(N,K),K=1,4),N=1,1)
 24       FORMAT(20X,'[',4F4,']',/)
          CALL SSP2TF(A,4,B,4,C,1,4,NUMR,DEN,INUM,IFAIL)
          WRITE(41,31)
 31       FORMAT(10X,'THE COEFICIENTS OF THE NUM IN TRANSFER FUNC',/)
          WRITE(41,11)(NUMR(I),I=1,INUM)
          WRITE(41,32)
 32       FORMAT(10X,'THE COEFICIENT OF THE DEN IN THE TRANSFER FUNC',/)
          WRITE(41,11)(DEN(I),I=1,5)
 11       FORMAT(/(1X,5F15.6))
          WRITE(41,98)
 98       FORMAT(1X,2(//////////))
          CALL F02AFF(H,4,4,RR,RI,INTEGE,0)
          WRITE(41,81)
 81       FORMAT(10X,'THE POLES OF THE MATRIX [A] ARE',/)
          WRITE(41,83) (RR(N),RI(N),N=1,4)
 83       FORMAT(10X,2F16.4)
          CALL C02AEF(DEN,5,REZ,IMZ,TOL,0)
          WRITE(41,75)
 75       FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE',/)
          WRITE(41,76) (REZ(N),IMZ(N),N=1,4)
 76       FORMAT(10X,2F16.4)
          CALL C02AEF(NUMR,INUM,RZ,IZ,TOL,0)
          WRITE(41,77)
 77       FORMAT(10X,'THE ZEROES OF THE TRANSFER FUNCTION ARE',/)
          WRITE(41,78) (RZ(I),IZ(I),I=1,2)
 78       FORMAT(10X,2F16.4)
          STOP
          END
C         ***************************************************
C         THIS SUBROUTINE DETERMINES THE COEFICIENTS OF NUM & DEN
C         OF THE TRANSFER FUNCTION.
C         ***************************************************
          SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
          REAL NUMR(5),DEN(5)
          REAL A(4,4),B(4,1),C(1,4),TMP1(4,4),TMP2(1,1),R(4,4)
          DATA EPS/0.000001/
          IFAIL = 1
          IF( N .LE. 0 ) RETURN
          IFAIL = 2
          DO 10 I = 1,N
            IF(B(I,1) .NE. 0.0) GOTO 36
 10       CONTINUE
          RETURN
 36       DO 20 I = 1,N
          DO 20 J = 1,N
            R(I,J) = 0.0
            R(I,I) = 1.0
 20       CONTINUE
          DEN(1) = 1.0
          DO 50 K = 1,N
          CALL F01CKF(TMP1,R,B,4,4,4,Z,1,1,0)
          CALL F01CKF(TMP2,C,TMP1,1,1,4,Z,1,1,0)
            NUMR(K) = TMP2(1,1)
          CALL F01CKF(TMP1,A,R,4,4,4,Z,1,1,0)
            ALPHAK = -TRACE(TMP1,4,4)/K
            DEN(K+1) = ALPHAK
            DO 40 I = 1,N
              DO 30 J = 1,N
                R(I,J) = TMP1(I,J)
          IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
 30           CONTINUE
 40         CONTINUE
```

```
50      CONTINUE
        DO 60 I = 1,N
          IF(ABS(NUMR(I)) .GT. EPS ) GOTO 22
60      CONTINUE
22      INUM = 0
        DO 70 J = I,N
          INUM = INUM + 1
          NUMR(INUM) = NUMR(J)
70      CONTINUE
        RETURN
        END
        FUNCTION TRACE(A,IA,N)
        REAL A(4,4)
        TRACE=0.0
        DO 56 I=1,N
        TRACE=TRACE+A(I,I)
56      CONTINUE
        RETURN
        END
```

```
*****************************************************
THE TRANSFER FUNCTION WR/WR* USING P CONTROLLER
*****************************************************

FREQ        SLIP        CURR        G1        G2

50.0000     0.0030      60.0000     1.3000    1.0000

            THE MATRIX [A11] IS

    -1.0000     0.0000     4.6167     0.0000
     0.0000     0.0408     0.0150     0.0000
     0.0000    -0.0150     0.0408     0.0000
     0.0000     0.0000     2.9167    -1.0000

  THE MATRIX [B] IS

    -8.5144
     0.0000
     0.9163
     0.0000

          THE STEADY STATE OPERATING POINT IS
VOLTAGE   IQRO          IDRO       TORQUE

165.14    -7.28         19.78      57.70
            THE MATRIX [A] IS

     -147.3790        3.8843     -474.8097     -164.0913
      136.0165       -6.1472      437.2607      171.2226
        0.8698        0.9425       -2.5623      -53.7826
        5.6266        0.0000       18.8174        0.0000

            THE MATRIX [B] IS

      134.1032
     -123.7642
        0.0000
        0.0000

            THE MATRIX [C] IS

            [ 0.  0.  0.  1.]

   THE COEFICIENTS OF THE NUM IN TRANSFER FUNC

754.539430    3866.788100   11248.514000
   THE COEFICIENT OF THE DEN IN THE TRANSFER FUNC

  1.000000    156.088500    2707.231300   17801.811000   22415.492000
```

THE POLES OF THE MATRIX [A] ARE

-137.3075	0.0000
-1.6224	0.0000
-8.5793	5.1979
-8.5793	-5.1979

THE POLES OF THE TRANSFER FUNCTION ARE

-137.3075	0.0000
-8.5793	-5.1979
-8.5793	5.1979
-1.6224	0.0000

THE ZEROES OF THE TRANSFER FUNCTION ARE

-2.5623	-2.8883
-2.5623	2.8883

```
C     ******************************************************************
C     THIS PROGRAM GETS THE TRANSFER FUNCTIONS WR/WR* , WR/WSL
C     WITH INDEPENDENT SPEED AND SLIP FREQUENCY CONTROL USING
C     PROPORTIONAL  (P) CONTROLLER.IT DETERMINES THE
C     POLES AND ZEROES OF THE ABOVE TRANSFER FUNCTIONS.
C     ******************************************************************
      DIMENSION A(4,4),WKSPCE(4),E(4,4),G(4,1),D(4,1)
      DIMENSION RR(4),RI(4),AA(4,4),BB(4,1),B(4,1)
      DIMENSION Z(1),INTEGE(4),C(1,4),NUMR(5),DEN(5)
      DIMENSION REZ(4),IMZ(4),RZ(4),IZ(4),H(4,4)
      REAL L1,L2
      OPEN(UNIT=40,DEVICE='DSK',FILE='INPUT.DAT')
      OPEN(UNIT=6,DEVICE='DSK',FILE='ERROR.DAT')
      OPEN(UNIT=41,DEVICE='DSK',FILE='OUTPUT.DAT')
      READ(40,*) ((E(IA,N),N=1,4),IA=1,4)
      READ(40,*) ((G(IB,M),IB=1,4),M=1,1)
      IA=4;IB=4;IC=1;N=4
      FQ=50;CIR=60;S=0.02;L1=1.3
C     READ(05,*) FQ,S,CIR,L1,L2
      READ(05,*) L2
      WRITE(05,*) FQ,S,CIR,L1,L2
      WRITE(41,97)
97    FORMAT(1X,///////)
      WRITE(41,95)
95    FORMAT(10X,'*********************************************',/)
      WRITE(41,94)
94    FORMAT(10X,'THE TRANSFER FUNCTION WR/WR* USING P CONTROLLER',/)
      WRITE(41,96)
96    FORMAT(10X,'*********************************************',/)
      WRITE(41,92)
92    FORMAT(10X,'FREQ',6X,'SLIP',6X,'CURR',6X,'G1',6X,'G2',/)
      WRITE(41,93) FQ,S,CIR,L1,L2
93    FORMAT(5X,5F10.4,/)
      CQS=1.10266*CIR;  P=4.0;WB=60.0*6.2832;WE=6.2832*FQ;RJ=0.31
      RS=0.0788;R2=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB
      FL=5.5/WB;RF=0.091;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1
      R1=RS+RF1;CL=(F*RL-CM*CM) ;WR=WE-S*WE;WSL=WE-WR
      E(1,3)=CM*WE; E(2,3)=RL*S*WE
      E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*CQS
      G(1,1)=-R1*CQS; G(3,1)=CM*S*CQS*WE
C     *********THE EQUATION IS [A11][X]=[B]*********************
      WRITE(41,12)
12    FORMAT(20X,'THE MATRIX [A11] IS',/)
      WRITE(41,13)((E(IA,N),N=1,4),IA=1,4)
13    FORMAT(10X,4F10.4/)
      WRITE(41,14)
14    FORMAT(10X,'THE MATRIX [B] IS',/)
      WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
15    FORMAT(10X,F10.4,/)
C     *********** FINDS STEADY STATE OPERATING POINT **************
      WRITE(41,19)
19    FORMAT(15X,'THE STEADY STATE OPERATING POINT IS')
      CALL F04AEF(E,4,G,4,4,1,D,4,WKSPCE,AA,4,BB,4,0)
      D(1,1)=1.654*D(1,1)
      WRITE(41,16)
16    FORMAT(4X,'VOLTAGE',4X,'IQRO',8X,'IDRO',5X,'TORQUE',/)
      WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
17    FORMAT(1X,4F10.2)
      R=R1+L1
C     R=R1
      A(1,1)=-(RL*R)/CL;A(1,2)=CM*R2/CL;A(1,3)=-CM*RL*WR/CL
      A(1,4)=-CM*RL*D(3,1)/CL-L1*RL/CL;A(2,1)=CM*R/CL;A(2,2)=-F*R2/CL
      A(2,3)=RL*F*WR/CL-WE;A(2,4)=(CM*CM*D(3,1)/CL)+L1*CM/CL
      A(3,1)=CM*WSL/RL;A(3,2)=WSL;A(3,3)=-R2/RL
      A(3,4)=0
      A(4,1)=3*P*P*CM*D(3,1)/(8*RJ);A(4,2)=0
      A(4,3)=(3*P*P*CM*CQS)/(8*RJ);A(4,4)=0
      DO 3 I=1,4
      DO 4 J=1,4
      H(I,J)=A(I,J)
4     CONTINUE
3     CONTINUE
      WRITE(41,73)
73    FORMAT(20X,'THE MATRIX [A] IS',/)
      WRITE(41,71) ((A(N,K),K=1,4),N=1,4)
```

```
FORMAT(10X,4F16.4,/)
B(1,1)=L1*L2*RL/CL;B(2,1)=-L1*L2*CM/CL;B(3,1)=0;B(4,1)=0
B(1,1)=RL/CL;B(2,1)=-CM/CL;B(3,1)=0;B(4,1)=0
B(1,1)=0;B(2,1)=-D(3,1);B(3,1)=(CM*COS+RL*D(2,1))/RL;B(4,1)=0
WRITE(41,21)
FORMAT(20X,'THE MATRIX [B] IS',/)
WRITE(41,38) ((B(N,K),K=1,1),N=1,4)
FORMAT(10X,F16.4,/)
C(1,1)=0;C(1,2)=0;C(1,3)=0;C(1,4)=1
C(1,1)=1;C(1,2)=0;C(1,3)=0;C(1,4)=0
WRITE(41,23)
FORMAT(20X,'THE MATRIX [C] IS',/)
WRITE(41,21) ((C(N,K),K=1,4),N=1,1)
FORMAT(20X,'[',4F4,']',/)
CALL SSP2TF(A,4,B,4,C,1,4,NUMR,DEN,INUM,IFAIL)
WRITE(41,31)
FORMAT(10X,'THE COEFICIENTS OF THE NUM IN TRANSFER FUNC',/)
WRITE(41,11)(NUMR(I),I=1,INUM)
WRITE(41,32)
FORMAT(10X,'THE COEFICIENT OF THE DEN IN THE TRANSFER FUNC',/)
WRITE(41,11)(DEN(I),I=1,5)
FORMAT(/(1X,5F15.6))
WRITE(41,98)
FORMAT(1X,2(//////////))
CALL F02AFF(H,4,4,RR,RI,INTEGE,0)
WRITE(41,81)
FORMAT(10X,'THE POLES OF THE MATRIX [A] ARE',/)
WRITE(41,83) (RR(N),RI(N),N=1,4)
FORMAT(10X,2F16.4)
CALL C02AEF(DEN,5,REZ,IMZ,TOL,0)
WRITE(41,75)
FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE',/)
WRITE(41,76) (REZ(N),IMZ(N),N=1,4)
FORMAT(10X,2F16.4)
CALL C02AEF(NUMR,INUM,RZ,IZ,TOL,0)
WRITE(41,77)
FORMAT(10X,'THE ZEROES OF THE TRANSFER FUNCTION ARE',/)
WRITE(41,78) (RZ(I),IZ(I),I=1,2)
FORMAT(10X,2F16.4)
STOP
END
****************************************************************
THIS SUBROUTINE DETERMINES THE COEFICIENTS OF NUM & DEN
OF THE TRANSFER FUNCTION.
****************************************************************
SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
REAL NUMR(5),DEN(5)
REAL A(4,4),B(4,1),C(1,4),TMP1(4,4),TMP2(1,1),R(4,4)
DATA EPS/0.000001/
IFAIL = 1
IF( N .LE. 0 ) RETURN
IFAIL = 2
DO 10 I = 1,N
  IF(B(I,1) .NE. 0.0) GOTO 36
CONTINUE
RETURN
DO 20 I = 1,N
DO 20 J = 1,N
  R(I,J) = 0.0
  R(I,I) = 1.0
CONTINUE
DEN(1) = 1.0
DO 50 K = 1,N
CALL F01CKF(TMP1,R,B,4,4,4,Z,1,1,0)
CALL F01CKF(TMP2,C,TMP1,1,1,4,Z,1,1,0)
  NUMR(K) = TMP2(1,1)
CALL F01CKF(TMP1,A,R,4,4,4,Z,1,1,0)
  ALPHAK = -TRACE(TMP1,4,4)/K
  DEN(K+1) = ALPHAK
  DO 40 I = 1,N
    DO 30 J = 1,N
      R(I,J) = TMP1(I,J)
IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
    CONTINUE
  CONTINUE
```

****

THE TRANSFER FUNCTION WR/WR* USING P CONTROLLER

****

FREQ	SLIP	CURR	G_1	G2
50.0000	0.0030	60.0000	1.3000	1.0000

THE MATRIX [A11] IS

-1.0000	0.0000	4.6167	0.0000
0.0000	0.0408	0.0150	0.0000
0.0000	-0.0150	0.0408	0.0000
0.0000	0.0000	2.9167	-1.0000

THE MATRIX [B] IS

-8.5144

0.0000

0.916[illegible]

0.0000

THE STEADY STATE OPERATING POINT IS

VOLTAGE	IQRO	IDRO	TORQUE
165.14	-7.28	19.78	57.70

THE MATRIX [A] IS

-147.3790	3.8843	-474.8097	-164.0913
136.0165	-6.1472	437.2607	151.4403
0.8698	0.9425	-2.5623	0.0000
5.6266	0.0000	18.8174	0.0000

THE MATRIX [B] IS

134.1032

-123.7642

0.0000

0.0000

THE MATRIX [C] IS

[0. 0. 0. 1.]

THE COEFICIENTS OF THE NUM IN TRANSFER FUNC

754.539430 3866.788100 11248.513000

THE COEFFICIENT OF THE DEN IN THE TRANSFER FUNC

1.000000 15[illegible].58500 1695.181700 6891.452300 13763.917000

THE POLES OF THE MATRIX [A] ARE

-144.6978	0.0000
-2.5177	2.9374
-2.5177	-2.9374
-6.3552	0.0000

THE POLES OF THE TRANSFER FUNCTION ARE

-144.6978	0.0000
-2.5177	-2.9374
-2.5177	2.9374
-6.3552	0.0000

THE ZEROES OF THE TRANSFER FUNCTION ARE

-2.5623	-2.8883
-2.5623	2.8883

```
CONTINUE
DO 60 I = 1,N
  IF(ABS(NUMR(I)) .GT. EPS ) GOTO 22
CONTINUE
INUM = 0
DO 70 J = 1,N
  INUM = INUM + 1
  NUMR(INUM) = NUMR(J)
CONTINUE
RETURN
END
FUNCTION TRACE(A,IA,N)
REAL A(4,4)
TRACE=0.0
DO 56 I=1,N
TRACE=TRACE+A(I,I)
CONTINUE
RETURN
END
```

```
C     ***************************************************************
C     THIS PROGRAM GETS THE TRANSFER FUNCTIONS WR/WR* , WR/WE
C     WITH INDEPENDENT SPEED AND FREQUENCY CONTROL USING PROPORTIONAL
C     PLUS INTEGRAL PROPORTIONAL CONTROLLER.IT ALSO DETERMINES THE
C     POLES AND ZEROES OF THE ABOVE TRANSFER FUNCTIONS.
C     ***************************************************************
      DIMENSION A(5,5),WKSPCE(4),E(4,4),G(4,1),D(4,1)
      DIMENSION RR(5),RI(5),AA(4,4),BB(4,1),B(5,1)
      DIMENSION Z(1),INTEGE(5),C(1,5),NUMR(6),DEN(6)
      DIMENSION REZ(5),IMZ(5),RZ(5),IZ(5),H(5,5)
      REAL L1,L2
      OPEN(UNIT=40,DEVICE='DSK',FILE='INPUT.DAT')
      OPEN(UNIT=6,DEVICE='DSK',FILE='ERROR.DAT')
      OPEN(UNIT=41,DEVICE='DSK',FILE='OUTPUT.DAT')
      READ(40,*) ((E(IA,N),N=1,4),IA=1,4)
      READ(40,*) ((G(IB,M),IB=1,4),M=1,1)
      IA=5;IB=5;IC=1;N=5
      FQ=50;CIR=60;S=0.003;L1=1.3
C     READ(05,*) FQ,S,CIR,L1,L2,T2
C     READ(05,*) L1
      WRITE(05,*) FQ,S,CIR,L1,L2,T2
      WRITE(41,97)
97    FORMAT(1X,///////)
      WRITE(41,95)
95    FORMAT(10X,'*********************************************',/
      WRITE(41,94)
94    FORMAT(10X,'THE TRANSFER FUNCTION WR/WR* USING PI CONTROLLER',/
      WRITE(41,96)
96    FORMAT(10X,'*********************************************',/
      WRITE(41,92)
92    FORMAT(10X,'FREQ',6X,'SLIP',6X,'CUR',6X,'G1',8X,'G2',8X,'T2',/)
      WRITE(41,93) FQ,S,CIR,L1,L2,T2
93    FORMAT(5X,6F10.4,/)
      CQS=1.10266*CIR;  P=4.0;WB=60.0*6.2832;WE=6.2832*FQ;RJ=0.31
      RS=0.0788;R2=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB
      FL=5.5/WB;RF=0.091;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1
      R1=RS+RF1;CL=(F*RL-CM*CM) ;WR=WE-S*WE;WSL=WE-WR
      E(1,3)=CM*WE; E(2,3)=RL*S*WE
      E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*CQS
      G(1,1)=-R1*CQS; G(3,1)=CM*S*CQS*WE
C     *******THE EQUATION IS [A11][X]=[B]*******************
      WRITE(41,12)
12    FORMAT(20X,'THE MATRIX [A11] IS',/)
      WRITE(41,13)((E(IA,N),N=1,4),IA=1,4)
13    FORMAT(10X,4F10.4/)
      WRITE(41,14)
14    FORMAT(/(10X,'THE MATRIX [B] IS'),/)
      WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
15    FORMAT(10X,F10.4,/)
C     *********** FINDS STEADY STATE OPERATING POINT *************
      WRITE(41,19)
19    FORMAT(/(15X,'THE STEADY STATE OPERATING POINT IS'))
      CALL F04AEF(E,4,G,4,4,1,D,4,WKSPCE,AA,4,BB,4,0)
      D(1,1)=1.654*D(1,1)
      WRITE(41,16)
16    FORMAT(4X,'VOLTAGE',4X,'IQRO',8X,'IDRO',5X,'TORQUE',/)
      WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
17    FORMAT(1X,4F10.2)
      R=R1+L1
C     R=R1
      A(1,1)=-(RL*R)/CL;A(1,2)=CM*R2/CL;A(1,3)=-CM*RL*WR/CL
      A(1,4)=L1*RL/CL;A(1,5)=-(CM*RL*D(3,1)/CL)-(L1*L2*T2*RL)/CL
      A(2,1)=CM*R/CL;A(2,2)=-F*R2/CL;A(2,4)=-L1*CM/CL
      A(2,3)=RL*F*WR/CL-WE;A(2,5)=(RL*F*D(3,1)/CL)+L1*L2*T2*CM/CL
      A(3,1)=CM*WSL/RL;A(3,2)=WSL;A(3,3)=-R2/RL;A(3,4)=0
      A(3,5)=-(CM*CQS+RL*D(2,1))/RL
C     A(3,4)=-(CM*CQS+RL*D(2,1))/RL
      A(4,1)=0;A(4,2)=0;A(4,3)=0;A(4,4)=0;A(4,5)=-L2
      A(5,1)=3*P*P*CM*D(3,1)/(8*RJ);A(5,2)=0
      A(5,3)=(3*P*P*CM*CQS)/(8*RJ);A(5,4)=0;A(5,5)=0
      DO 3 I=1,N
      DO 4 J=1,N
      H(I,J)=A(I,J)
4     CONTINUE
3     CONTINUE
      WRITE(41,73)
```

```
73     FORMAT(/(20X,'THE MATRIX [A] IS'),/)
       WRITE(41,74) ((A(N,K),K=1,5),N=1,5)
74     FORMAT(1X,5F14.4,/)
C      B(1,1)=L1*RL/CL;B(2,1)=-L1*CM/CL;B(3,1)=0;B(4,1)=0
C      B(1,1)=RL/CL;B(2,1)=-CM/CL;B(3,1)=0;B(4,1)=0
C      B(1,1)=0;B(2,1)=-D(3,1);B(3,1)=(CM*COS+RL*D(2,1))/RL;B(4,1)=0
       B(1,1)=L1*L2*T2*RL/CL;B(2,1)=-L1*L2*T2*CM/CL;B(3,1)=0
       B(4,1)=L2;B(5,1)=0
       WRITE(41,21)
21     FORMAT(/(20X,'THE MATRIX [B] IS'),/)
       WRITE(41,38) ((B(N,K),K=1,1),N=1,5)
38     FORMAT(10X,F16.4,/)
       C(1,1)=0;C(1,2)=0;C(1,3)=0;C(1,4)=0;C(1,5)=1
C      C(1,1)=1;C(1,2)=0;C(1,3)=0;C(1,4)=0
       WRITE(41,23)
23     FORMAT(20X,'THE MATRIX [C] IS',/)
       WRITE(41,24) ((C(N,K),K=1,5),N=1,1)
24     FORMAT(20X,'['5F5,']',/)
       CALL SSP2TF(A,5,B,5,C,1,5,NUMR,DEN,INUM,IFAIL)
       WRITE(41,31)
31     FORMAT(/(10X,'THE COEFICIENTS OF THE NUM IN TRANSFER FUNC'),/)
       WRITE(41,11)(NUMR(I),I=1,INUM)
       WRITE(41,98)
98     FORMAT(1X,2(///////))
       WRITE(41,32)
32     FORMAT(/(10X,'THE COEF OF THE DEN IN THE TRANSFER FUNC'),/)
       WRITE(41,11)(DEN(I),I=1,6)
11     FORMAT(1X,F15.6,/)
       CALL F02AFF(H,5,5,RR,RI,INTEGE,0)
       WRITE(41,81)
81     FORMAT(/(10X,'THE POLES OF THE MATRIX [A] ARE'),/)
       WRITE(41,83) (RR(N),RI(N),N=1,5)
83     FORMAT(10X,2F16.4)
       CALL C02AEF(DEN,6,REZ,IMZ,TOL,0)
       WRITE(41,75)
75     FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE',/)
       WRITE(41,76) (REZ(N),IMZ(N),N=1,5)
76     FORMAT(10X,2F16.4)
       CALL C02AEF(NUMR,INUM,RZ,IZ,TOL,0)
       WRITE(41,77)
77     FORMAT(/(10X,'THE ZEROES OF THE TRANSFER FUNCTION ARE'),/)
       WRITE(41,78) (RZ(I),IZ(I),I=1,3)
78     FORMAT(10X,2F16.4)
       STOP
       END
C      *****************************************************************
C      THIS SUBROUTINE DETERMINES THE COEFICIENTS OF NUM & DEN
C      OF THE TRANSFER FUNCTION.
C      *****************************************************************
       SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
       REAL NUMR(6),DEN(6)
       REAL A(5,5),B(5,1),C(1,5),TMP1(5,5),TMP2(1,1),R(5,5)
       DATA EPS/0.000001/
       IFAIL = 1
       IF( N .LE. 0 ) RETURN
       IFAIL = 2
       DO 10 I = 1,N
         IF(B(I,1) .NE. 0.0) GOTO 36
10     CONTINUE
       RETURN
36     DO 20 I = 1,N
       DO 20 J = 1,N
         R(I,J) = 0.0
         R(I,I) = 1.0
20     CONTINUE
       DEN(1) = 1.0
       DO 30 K = 1,N
       CALL F01CKF(TMP1,R,B,5,5,5,Z,1,1,0)
       CALL F01CKF(TMP2,C,TMP1,1,1,5,Z,1,1,0)
         NUMR(K) = TMP2(1,1)
       CALL F01CKF(TMP1,A,R,5,5,5,Z,1,1,0)
         ALPHAK = -TRACE(TMP1,5,5)/K
         DEN(K+1) = ALPHAK
         DO 40 I = 1,N
           DO 30 J = 1,N
```

```
              R(I,J) = TMP1(I,J)
          IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
   30         CONTINUE
   40       CONTINUE
   50     CONTINUE
          DO 60 I = 1,N
            IF(ABS(NUMR(I)) .GT. EPS ) GOTO 22
   60     CONTINUE
   22     INUM = 0
          DO 70 J = 1,N
            INUM = INUM + 1
            NUMR(INUM) = NUMR(J)
   70     CONTINUE
          RETURN
          END
          FUNCTION TRACE(A,IA,N)
          REAL A(5,5)
          TRACE=0.0
          DO 56 I=1,N
          TRACE=TRACE+A(I,I)
   56     CONTINUE
          RETURN
          END
```

```
***************************************************
THE TRANSFER FUNCTION WR/WR* USING PI CONTROLLER
***************************************************
  FREQ        SLIP       CUR        G1         G2         T2
50.0000     0.0030    60.0000     1.3000     1.0000     0.1000
          THE MATRIX [A11] IS
    -1.0000     0.0000     4.6167     0.0000
     0.0000     0.0408     0.0150     0.0000
     0.0000    -0.0150     0.0408     0.0000
     0.0000     0.0000     2.9167    -1.0000

THE MATRIX [B] IS
    -8.5144
     0.0000
     0.9163
     0.0000

          THE STEADY STATE OPERATING POINT IS
VOLTAGE     IQRO         IDRO       TORQUE
165.14      -7.28        19.78       57.70
          THE MATRIX [A] IS
 -147.3790       3.8843    -474.8097     134.1032     -43.3984
  136.9165      -6.1472     437.2607    -123.7642      59.8348
    0.8698       0.9425      -2.5623       0.0000     -53.7826
    0.0000       0.0000       0.0000       0.0000      -1.0000
    5.6266       0.0000      18.8174       0.0000       0.0000
          THE MATRIX [B] IS
           13.4103
          -12.3764
            0.0000
            1.0000
            0.0000
            THE MATRIX [C] IS
            [  0.  0.  0.  0.  1.]

     THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC
   75.453942
 1141.218200
 4991.539500
11248.559000
```

THE COEF OF THE DEN IN THE TRANSFER FUNC

```
    1.000000
  156.088500
 2028.145800
15076.242000
16158.606000
11248.716000
```

THE POLES OF THE MATRIX [A] ARE

```
-142.6019      0.0000
  -6.1774      7.2051
  -6.1774     -7.2051
  -0.5659      0.7453
  -0.5659     -0.7453
```

THE POLES OF THE TRANSFER FUNCTION ARE

```
-142.6019      0.0000
  -6.1774     -7.2051
  -6.1774      7.2051
  -0.5659     -0.7453
  -0.5659      0.7453
```

THE ZEROES OF THE TRANSFER FUNCTION ARE

```
 -10.0000      0.0000
  -2.5623     -2.8883
  -2.5623      2.8883
```

```
C     ***************************************************************
C     THIS PROGRAM GETS THE TRANSFER FUNCTIONS WR/WR* , WR/WSL
C     WITH INDEPENDENT SPEED AND SLIP FREQUENCY CONTROL USING
C     PROPORTIONAL PLUS INTEGRAL (PI) CONTROLLER.IT DETERMINES THE
C     POLES AND ZEROES OF THE ABOVE TRANSFER FUNCTIONS.
C     ***************************************************************
      DIMENSION A(5,5),WKSPCE(4),E(4,4),G(4,1),D(4,1)
      DIMENSION RR(5),RI(5),AA(4,4),BB(4,1),B(5,1)
      DIMENSION Z(1),INTEGE(5),C(1,5),NUMR(6),DEN(6)
      DIMENSION REZ(5),IMZ(5),RZ(5),IZ(5),H(5,5)
      REAL L1,L2
      OPEN(UNIT=40,DEVICE='DSK',FILE='INPUT.DAT')
      OPEN(UNIT=6,DEVICE='DSK',FILE='ERROR.DAT')
      OPEN(UNIT=41,DEVICE='DSK',FILE='OUTPUT.DAT')
      READ(40,*) ((E(IA,N),N=1,4),IA=1,4)
      READ(40,*) ((G(IB,M),IB=1,4),M=1,1)
      IA=5;IB=5;IC=1;N=5
      FQ=50;CIR=60;S=0.02;L1=1.3;T2=0.1
C     READ(05,*) FQ,S,CIR,L1,L2,T2
      READ(05,*) L2
      WRITE(05,*) FQ,S,CIR,L1,L2,T2
      WRITE(41,97)
97    FORMAT(1X,///////)
      WRITE(41,95)
95    FORMAT(10X,'*******************************************',/)
      WRITE(41,94)
94    FORMAT(10X,'THE TRANSFER FUNCTION WR/WR* USING PI CONTROLLER',/)
      WRITE(41,96)
96    FORMAT(10X,'*******************************************',/)
      WRITE(41,92)
92    FORMAT(10X,'FREQ',6X,'SLIP',6X,'CUR',6X,'G1',8X,'G2',8X,'T2',/)
      WRITE(41,93) FQ,S,CIR,L1,L2,T2
93    FORMAT(5X,6F10.4,/)
      CQS=1.10266*CIR;  P=4.0;WB=60.0*6.2832;WE=6.2832*FQ;RJ=0.31
      RS=0.0788;R2=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB
      FL=5.5/WB;RF=0.091;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1
      R1=RS+RF1;CL=(F*RL-CM*CM) ;WR=WE-S*WE;WSL=WE-WR
      E(1,3)=CM*WE; E(2,3)=RL*S*WE
      E(3,2)=-RL*S*WE; E(4,3)=0.75*P*CM*CQS
      G(1,1)=-R1*CQS; G(3,1)=CM*S*CQS*WE
C     ******THE EQUATION IS [A11][X]=[B]*******************
      WRITE(41,12)
12    FORMAT(20X,'THE MATRIX [A11] IS',/)
      WRITE(41,13)((E(IA,N),N=1,4),IA=1,4)
13    FORMAT(10X,4F10.4/)
      WRITE(41,14)
14    FORMAT(/(10X,'THE MATRIX [B] IS'),/)
      WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
15    FORMAT(10X,F10.4,/)
C     ********** FINDS STEADY STATE OPERATING POINT *************
      WRITE(41,19)
19    FORMAT(/(15X,'THE STEADY STATE OPERATING POINT IS'))
      CALL F04AEF(E,4,G,4,4,1,D,4,WKSPCE,AA,4,BB,4,0)
      D(1,1)=1.654*D(1,1)
      WRITE(41,16)
16    FORMAT(4X,'VOLTAGE',4X,'IQRD',8X,'IDRO',5X,'TORQUE',/)
      WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
17    FORMAT(1X,4F10.2)
      R=R1+L1
C     R=R1
      A(1,1)=-(RL*R)/CL;A(1,2)=CM*R2/CL;A(1,3)=-CM*RL*WR/CL
      A(1,4)=L1*RL/CL;A(1,5)=-(CM*RL*D(3,1)/CL)-(L1*L2*T2*RL)/CL
      A(2,1)=CM*R/CL;A(2,2)=-F*R2/CL;A(2,4)=-L1*CM/CL
      A(2,3)=RL*F*WR/CL-WE;A(2,5)=(CM*CM*D(3,1)/CL)+L1*L2*T2*CM/CL
      A(3,1)=CM*WSL/RL;A(3,2)=WSL;A(3,3)=-R2/RL;A(3,4)=0
      A(3,5)=0
C     A(3,1)=-(CM*CQS+RL*D(2,1))/RL
      A(4,1)=0;A(4,2)=0;A(4,3)=0;A(4,4)=0;A(4,5)=-L2
      A(5,1)=3*P*P*CM*D(3,1)/(8*RJ);A(5,2)=0
      A(5,3)=(3*P*P*CM*CQS)/(8*RJ);A(5,4)=0;A(5,5)=0
      DO 3 I=1,N
      DO 4 J=1,N
      H(I,J)=A(I,J)
4     CONTINUE
```

```
3     CONTINUE
      WRITE(41,73)
73    FORMAT(/(20X,'THE MATRIX [A] IS'),/)
      WRITE(41,74) ((A(N,K),K=1,5),N=1,5)
74    FORMAT(1X,5F14.4,/)
C     B(1,1)=L1*RL/CL;B(2,1)=-L1*CM/CL;B(3,1)=0;B(4,1)=0
C     B(1,1)=RL/CL;B(2,1)=-CM/CL;B(3,1)=0;B(4,1)=0
C     B(1,1)=0;B(2,1)=-D(3,1);B(3,1)=(CM*COS+RL*D(2,1))/RL;B(4,1)=0
C     B(5,1)=0
      B(1,1)=L1*L2*T2*RL/CL;B(2,1)=-L1*L2*T2*CM/CL;B(3,1)=0
      B(4,1)=L2;B(5,1)=0
      WRITE(41,21)
21    FORMAT(/(20X,'THE MATRIX [B] IS'),/)
      WRITE(41,38) ((B(N,K),K=1,1),N=1,5)
38    FORMAT(10X,F16.4,/)
      C(1,1)=0;C(1,2)=0;C(1,3)=0;C(1,4)=0;C(1,5)=1
C     C(1,1)=1;C(1,2)=0;C(1,3)=0;C(1,4)=0
      WRITE(41,23)
23    FORMAT(20X,'THE MATRIX [C] IS',/)
      WRITE(41,24) ((C(N,K),K=1,5),N=1,1)
24    FORMAT(20X,'['5F5,']',/)
      CALL SSP2TF(A,5,B,5,C,1,5,NUMR,DEN,INUM,IFAIL)
      WRITE(41,31)
31    FORMAT(/(10X,'THE COEFICIENTS OF THE NUM IN TRANSFER FUNC'),/)
      WRITE(41,11)(NUMR(I),I=1,INUM)
      WRITE(41,98)
98    FORMAT(1X,2(///////))
      WRITE(41,32)
32    FORMAT(/(10X,'THE COEF OF THE DEN IN THE TRANSFER FUNC'),/)
      WRITE(41,11)(DEN(I),I=1,6)
11    FORMAT(1X,F15.6,/)
      CALL F02AFF(H,5,5,RR,RI,INTEGE,0)
      WRITE(41,81)
81    FORMAT(/(10X,'THE POLES OF THE MATRIX [A] ARE'),/)
      WRITE(41,83) (RR(N),RI(N),N=1,5)
83    FORMAT(10X,2F16.4)
      CALL C02AEF(DEN,6,REZ,IMZ,TOL,0)
      WRITE(41,75)
75    FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE',/)
      WRITE(41,76) (REZ(N),IMZ(N),N=1,5)
76    FORMAT(10X,2F16.4)
      CALL C02AEF(NUMR,INUM,RZ,IZ,TOL,0)
      WRITE(41,77)
77    FORMAT(/(10X,'THE ZEROES OF THE TRANSFER FUNCTION ARE'),/)
      WRITE(41,78) (RZ(I),IZ(I),I=1,3)
78    FORMAT(10X,2F16.4)
      STOP
      END
C     ***************************************************************
C     THIS SUBROUTINE DETERMINES THE COEFICIENTS OF NUM & DEN
C     OF THE TRANSFER FUNCTION.
C     ***************************************************************
      SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
      REAL NUMR(6),DEN(6)
      REAL A(5,5),B(5,1),C(1,5),TMP1(5,5),TMP2(1,1),R(5,5)
      DATA EPS/0.000001/
      IFAIL = 1
      IF( N .LE. 0 ) RETURN
      IFAIL = 2
      DO 10 I = 1,N
        IF(B(I,1) .NE. 0.0) GOTO 36
10    CONTINUE
      RETURN
36    DO 20 I = 1,N
      DO 20 J = 1,N
        R(I,J) = 0.0
        R(I,I) = 1.0
20    CONTINUE
      DEN(1) = 1.0
      DO 50 K = 1,N
      CALL F01CKF(TMP1,R,B,5,5,5,Z,1,1,0)
      CALL F01CKF(TMP2,C,TMP1,1,1,5,Z,1,1,0)
        NUMR(K) = TMP2(1,1)
      CALL F01CKF(TMP1,A,R,5,5,5,Z,1,1,0)
        ALPHAK = -TRACE(TMP1,5,5)/K
        DEN(K+1) = ALPHAK
```

```
            DO 40 I = 1,N
              DO 30 J = 1,N
                R(I,J) = TMP1(I,J)
            IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
  30          CONTINUE
  40        CONTINUE
  50      CONTINUE
          DO 60 I = 1,N
            IF(ABS(NUMR(I)) .GT. EPS ) GOTO 22
  60      CONTINUE
  22      INUM = 0
          DO 70 J = I,N
            INUM = INUM + 1
            NUMR(INUM) = NUMR(J)
  70      CONTINUE
          RETURN
          END
          FUNCTION TRACE(A,IA,N)
          REAL A(5,5)
          TRACE=0.0
          DO 56 I=1,N
          TRACE=TRACE+A(I,I)
  56      CONTINUE
          RETURN
          END
```

```
*********************************************************
THE TRANSFER FUNCTION WR/WR* USING PI CONTROLLER
*********************************************************
  FREQ        SLIP       CUR        G1         G2         T2
 50.0000     0.0030    60.0000    1.3000     1.0000     0.1000

              THE MATRIX [A11] IS
     -1.0000     0.0000     4.6167     0.0000
      0.0000     0.0408     0.0150     0.0000
      0.0000    -0.0150     0.0408     0.0000
      0.0000     0.0000     2.9167    -1.0000

   THE MATRIX [B] IS
     -8.5144
      0.0000
      0.9163
      0.0000

              THE STEADY STATE OPERATING POINT IS
 VOLTAGE      IQRO          IDRO       TORQUE
  165.14      -7.28        19.78       57.70
              THE MATRIX [A] IS
  -147.3790      3.8843    -474.8097     134.1032    -43.3984
   136.0165     -6.1472     437.2607    -123.7642     40.0525
     0.8698      0.9425      -2.5623       0.0000      0.0000
     0.0000      0.0000       0.0000       0.0000     -1.0000
     5.6266      0.0000      18.8174       0.0000      0.0000
              THE MATRIX [B] IS
             13.4103
            -12.3764
              0.0000
              1.0000
              0.0000
              THE MATRIX [C] IS
              [   0.    0.    0.    0.    1.]

   THE COEFFICIENTS OF THE NUM IN TRANSFER FUNC
    75.453942
  1141.218200
  4991.639300
 11248.537000
```

```
THE COEF OF THE DEN IN THE TRANSFER FUNC

    1.000000

  156.088500

 1016.096200

 4165.882400

 7507.040200

11247.378000

THE POLES OF THE MATRIX [A] ARE

       -149.4750          0.0000
         -2.4854          2.7959
         -2.4854         -2.7959
         -0.8214          2.1686
         -0.8214         -2.1686
THE POLES OF THE TRANSFER FUNCTION ARE

       -149.4750          0.0000
         -2.4852         -2.7959
         -2.4852          2.7959
         -0.8215         -2.1685
         -0.8215          2.1685

THE ZEROES OF THE TRANSFER FUNCTION ARE

        -10.0000          0.0000
         -2.5623         -2.8883
         -2.5623          2.8883
```

```
 13     FORMAT(10X,4F10.4/)
        WRITE(41,14)
 14     FORMAT(10X,'THE MATRIX [B11] IS',/)
        WRITE(41,15) ((G(IB,M),M=1,1),IB=1,4)
 15     FORMAT(10X,F10.4,/)
        WRITE(41,19)
 19     FORMAT(15X,'THE STEADY STATE OPERATING POINT IS')
        WRITE(41,16)
 16     FORMAT(4X,'VOLTAGE',4X,'IQRO',8X,'IDRO',5X,'TORQUE',/)
        WRITE(41,17) ((D(IC,M),IC=1,4),M=1,1)
 17     FORMAT(1X,4F10.2)
        WRITE(41,73)
 73     FORMAT(20X,'THE MATRIX [A] IS',/)
        WRITE(41,74) ((A(N,K),K=1,4),N=1,4)
 74     FORMAT(10X,4F16.4,/)
        WRITE(41,21)
 21     FORMAT(20X,'THE MATRIX [B] IS',/)
        WRITE(41,38) ((B(N,K),K=1,1),N=1,4)
 38     FORMAT(10X,F16.4,/)
        WRITE(41,23)
 23     FORMAT(20X,'THE MATRIX [C] IS',/)
        WRITE(41,24) ((C(N,K),K=1,4),N=1,1)
 24     FORMAT(20X,'[',4F4,']',/)
        CALL SSP2TF(A,4,B,4,C,1,4,NUMR,DEN,INUM,IFAIL)
        WRITE(41,31)
 31     FORMAT(10X,'THE COEFICIENTS OF THE NUM IN TRANSFER FUNC',/)
        WRITE(41,11)(NUMR(I),I=1,INUM)
        WRITE(41,32)
 32     FORMAT(10X,'THE COEFICIENT OF THE DEN IN THE TRANSFER FUNC',/)
        WRITE(41,11)(DEN(I),I=1,5)
 11     FORMAT(/(1X,5F15.6))
        CALL ROUTH(PQ,WSL,L1,CI,E,G,D,A,H,B,C,D3,D4,H3,H4,D1)
        CALL F02AFF(H,4,4,RR,RI,INTEGE,0)
        WRITE(41,81)
 81     FORMAT(10X,'THE POLES OF THE MATRIX [A] ARE',/)
        WRITE(41,84) (RR(N),RI(N),N=1,4)
 84     FORMAT(10X,2F16.4)
        CALL C02AEF(DEN,5,REZ,IMZ,TOL,0)
        WRITE(41,75)
 75     FORMAT(10X,'THE POLES OF THE TRANSFER FUNCTION ARE',/)
        WRITE(41,76) (REZ(N),IMZ(N),N=1,4)
 76     FORMAT(10X,2F16.4)
        CALL C02AEF(NUMR,INUM,RZ,IZ,TOL,0)
        WRITE(41,77)
 77     FORMAT(10X,'THE ZEROES OF THE TRANSFER FUNCTION ARE',/)
        WRITE(41,78) (RZ(I),IZ(I),I=1,4)
 78     FORMAT(10X,2F16.4)
        WRITE(41,56)
 56     FORMAT(1X,'THE MATRIX [D3] IS',/)
        WRITE(41,53) ((H3(N,K),K=1,3),N=1,3)
 53     FORMAT(1X,3F14.4,/)
        WRITE(41,57)
 57     FORMAT(1X,'THE MATRIX [D4] IS',/)
        WRITE(41,54) ((H4(N,K),K=1,4),N=1,4)
 54     FORMAT(1X,4F14.4,/)
        WRITE(41,58)
 58     FORMAT(1X,'THE VALUES OF DETERMINANTS D1--D4 ARE',/)
        WRITE(41,55) (D1(N),N=1,4)
 55     FORMAT(1X,4F25.4)
        CONTINUE
 1      CONTINUE
 2      CONTINUE
 5      CONTINUE
        STOP
        END
C       ****************************************************************
C       THIS SUBROUTINE DETERMINES THE TRANSFER FUNCTION FOR THE
C       GIVEN [A], [B] AND [C] USING THE LEVRRIER-FADDEEV METHOD
C       ****************************************************************
        SUBROUTINE SSP2TF(A,IA,B,IB,C,IC,N,NUMR,DEN,INUM,IFAIL)
        REAL NUMR(5),DEN(5)
        REAL A(4,4),B(4,1),C(1,4),TMP1(4,4),TMP2(1,1),R(4,4)
        DATA EPS/0.000001/
        IFAIL = 1
        IF( N .LE. 0 ) RETURN
        IFAIL = 2
        DO 10 I = 1,N
          IF(B(I,1) .NE. 0.0) GOTO 36
 10     CONTINUE
        RETURN
```

```
36      DO 20 I = 1,N
        DO 20 J = 1,N
          R(I,J) = 0.0
          R(I,I) = 1.0
20      CONTINUE
        DEN(1) = 1.0
        DO 50 K = 1,N
        CALL F01CKF(TMP1,R,B,4,4,4,Z,1,1,0)
        CALL F01CKF(TMP2,C,TMP1,1,1,4,Z,1,1,0)
          NUMR(K) = TMP2(1,1)
        CALL F01CKF(TMP1,A,R,4,4,4,Z,1,1,0)
          ALPHAK = -TRACE(TMP1,4,4)/K
          DEN(K+1) = ALPHAK
          DO 40 I = 1,N
            DO 30 J = 1,N
              R(I,J) = TMP1(I,J)
        IF(I.EQ.J) R(I,I)=R(I,I)+ALPHAK
30          CONTINUE
40        CONTINUE
50      CONTINUE
        DO 60 I = 1,N
          IF(ABS(NUMR(I)) .GT. EPS ) GOTO 22
60      CONTINUE
22      INUM = 0
        DO 70 J = I,N
          INUM = INUM + 1
          NUMR(INUM) = NUMR(J)
70      CONTINUE
        RETURN
        END
        FUNCTION TRACE(A,IA,N)
        REAL A(4,4)
        TRACE=0.0
        DO 56 I=1,N
        TRACE=TRACE+A(I,I)
56      CONTINUE
        RETURN
        END
C       ****************************************************************
C       THIS SUBROUTINE GIVES THE VALUES DETERMINANTS D1,D2,D3 & D4.
C       ****************************************************************
        SUBROUTINE ROUTH(FQ,WSL,L1,CIR,E,G,D,A,H,B,C,D3,D4,H3,H4,D1)
        DIMENSION A(4,4),WKSPCE(4),E(4,4),G(4,1),D(4,1)
        DIMENSION RR(4),RI(4),AA(4,4),BB(4,1),B(4,1)
        DIMENSION Z(1),INTEGE(4),C(1,4),NUMR(5),DEN(5)
        DIMENSION REZ(4),IMZ(4),RZ(4),IZ(4),H(4,4)
        DIMENSION D1(4),D3(3,3),D4(4,4),H3(3,3),H4(4,4)
        REAL L1
        COS=1.10266*CIR;  P=4.0;WB=60.0*6.2832;WE=6.2832*FQ;RJ=0.31
        RS=0.0788;R2=0.0408;SL=5.7518/WB;RL=6.0028/WB;CM=5.54/WB
        FL=5.5/WB;RF=0.091;RF1=0.5483*RF;FL1=0.5483*FL;F=SL+FL1
        R1=RS+RF1;CL=(F*RL-CM*CM) ;WR=WE-WSL
        E(1,3)=CM*WE; E(2,3)=RL*WSL
        E(3,2)=-RL*WSL; E(4,3)=0.75*P*CM*COS
        G(1,1)=-R1*COS; G(3,1)=CM*COS*WSL
C       ******THE EQUATION IS [A1][X]=[B]*******************
C       *********** FINDS STEADY STATE OPERATING POINT *******
        CALL F04AEF(E,4,G,4,4,1,D,4,WKSPCE,AA,4,BB,4,0)
        D(1,1)=1.654*D(1,1)
        R=R1+L1
        A(1,1)=-(RL*R)/CL;A(1,2)=CM*R2/CL;A(1,3)=-CM*RL*WR/CL
        A(1,4)=-CM*RL*D(3,1)/CL;A(2,1)=CM*R/CL;A(2,2)=-F*R2/CL
        A(2,3)=RL*F*WR/CL-WE;A(2,4)=(RL*F*D(3,1)/CL)
        A(3,1)=CM*WSL/RL;A(3,2)=WSL;A(3,3)=-R2/RL
        A(3,4)=-(CM*COS+RL*D(2,1))/RL
        A(4,1)=3*P*P*CM*D(3,1)/(8*RJ);A(4,2)=0
        A(4,3)=(3*P*P*CM*COS)/(8*RJ);A(4,4)=0
        DO 3 I=1,N
        DO 4 J=1,N
        H(I,J)=A(I,J)
4       CONTINUE
3       CONTINUE
        B(1,1)=L1*RL/CL;B(2,1)=-L1*CM/CL;B(3,1)=0;B(4,1)=0
C       B(1,1)=0;B(2,1)=-D(3,1);B(3,1)=(CM*COS+RL*D(2,1))/RL
C       B(4,1)
```